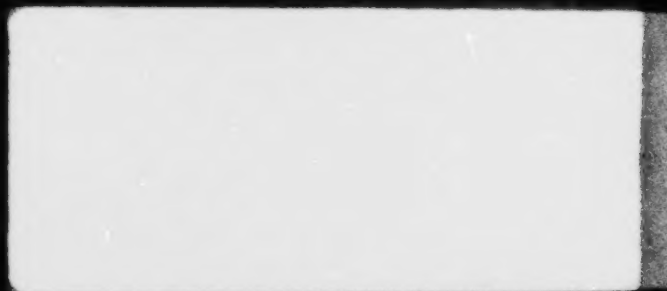


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FINAL REPORT

BY

S.R. Bala and S. Pond

**AMCA International Limited
Research and Technology Centre**

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EXECUTIVE SUMMARY

Formability and hydrogen induced cold cracking susceptibility (weldability) of two steels, with potential applications in offshore structures and Arctic vessels, have been examined. The two steels were: ASTM A710 Gr. A Cl. 3, and Algoma's LT 60 steel. The latter was a production level special heat, and it also meets the requirements of CSA Standard G40.21 Gr. 350 WT. For the weldability study, BS 4360 Gr. 50 E steel was included as a reference, similar steels having been extensively used in the North Sea environment.

Since most offshore production platforms employ tubular construction requiring forming of plates into cans, and since these structures would be operating at low ambient temperatures, the emphasis of the formability study was on the effect of roll forming strain, and subsequent fabrication thermal cycles on mechanical properties, especially toughness.

In the study, the two steels were subjected to strains of 0 (as received condition), and approximately 3 and 6%. The mechanical property evaluation was carried out in the as formed condition, as well as after subjecting the formed steel to the following heat treatments: strain aged at 250° or 370°C, stress relieved at 620°C, and strain aged at 370°C + stress relieved conditions. The mechanical property evaluation included tensile properties, CVN toughness and crack tip opening displacement (CTOD) testing at -50° to -60°C for selected conditions - all in the longitudinal direction.

The results indicate that the Algoma LT 60 steel generally had excellent toughness. The lowest CVN energy absorbed at -60°C , considering all the conditions tested, was 86 J in the roll formed (6%) + strain aged + stress relieved condition. The corresponding average CTOD value at -60°C was 0.29 mm, with predominantly ductile tearing in the crack initiation region.

The performance of the A710 Gr. A Cl. 3 steel was not as good. Roll forming led to a progressive decrease in the CVN energy absorbed at -60°C . However, the stress relief treatment always restored the CVN toughness to a level equal to or better than that of the as received material (> 180 J at -60°C). The CTOD test at -60°C , after stress relief, showed occasional brittle behaviour; at -50°C , however, the CTOD values were greater than 0.5 mm after stress relief. In terms of CVN toughness, the performance of the steel has been lower than expected since in an earlier study, even after a 7% strain, the energy absorbed at -60°C exceeded 125 J. It is believed that the A710 Gr. A Cl. 3 steel employed in the investigation had not been optimally heat treated vis a vis its impact strength.

For the weldability evaluation, four types of tests were carried out viz. hardening curves to determine the heat affected zone hardness as a function of heat input; Tekken and Controlled Thermal Severity (CTS) tests to examine the effect of preheat on cold cracking; and implant tests to determine the lower critical stress for each steel.

The results from the four types of tests all lead to a similar conclusion that although the BS 4360 Gr 50 E reference steel has controlled carbon equivalent and good resistance to cold cracking as indicated by its successful fabrication in the North Sea applications, the two candidate steels have higher resistance to cold cracking. Between these two, A710 Gr. A Cl. 3 has higher resistance to cold cracking than does the Algoma LT 60 steel. As a matter of fact, the A710 steel, from the point of view of heat affected zone, could probably be welded at room temperature without preheat, although to prevent cold cracking in weld metal some preheat may still be required.

Since the evaluation of steels for offshore and arctic structures must include additional considerations such as HAZ toughness, weld corrosion, etc., no general conclusions can be drawn at this stage.

From the point of view of parent material weldability alone, the steels investigated are believed to be superior to BS4360 Gr 50E, and suitable for the intended applications.

Regarding the effect of forming on toughness of parent plate, which is of relevance to offshore tubular structures only, the Algoma LT60 steel seems to be better than the ASTM A710 Gr A Cl 3, and quite suitable for offshore structures. However, it must be cautioned that the former was from an experimental heat, whereas, the A710 steel plates were a typical commercial product.

PART A: "AN INVESTIGATION INTO THE FORMABILITY OF TWO
CANDIDATE STEELS"

by Sathish Rao Bala

1. INTRODUCTION

The environmental conditions, especially the ambient temperature, in the regions where the Canadian Offshore hydrocarbons are located, are unique and there is little past experience on suitability and adequacy of steels for structures in these environments. For submerged parts of these structures, the design temperature is around 0°C, and steels similar to those used in the North Sea, such as modified Canadian steel CSA G40.21 Gr 350WT, should be adequate for this purpose.

However, for steel structures exposed to the ambient air temperature, the design temperature could be in the range -30° to -60°C⁽¹⁾. A steel such as CSA G40.21 Gr 350WT or BS4360 Gr 50D is unlikely to possess adequate fracture toughness at these temperatures, especially in the HAZ, and therefore improved steels would have to be used for above waterline portions of some of these structures.

The offshore production platforms constitute a large number of tubular structural members whose diameters can be as high as 10m at the node region with wall thickness up to 150mm^(2,3). In heavy industries involved in the fabrication of pressure vessels, tubulars, etc., it is a common practice to employ three-roll-forming to bend steel plates into cylindrical shapes. The bending operation can be performed with

plates at room temperature (cold) or at higher temperatures (warm or hot); however, cold roll-forming is the preferred process.

The inherent advantages of cold roll-forming are greater dimensional accuracy, more comfortable working environment, energy and cost savings, etc. Based on past experience, or per code requirements, the maximum safe outer fibre strain of such cold roll-formed plates is normally 5-7% or less. Depending on the composition and structure, the steel would undergo deterioration in impact energy with increasing outer fibre strain. Since these tubulars are to be welded, strain-aging due to the weld thermal cycle can further embrittle the steel whereas stress relieving may ameliorate part or whole of this damage. These effects would be more prominent near the tension surface of the formed plate. Consequently, various Regulating Bodies⁽⁴⁾ limit the circumferential strain to rather low values, exceeding which heat treatments such as stress relieving, normalizing, etc. are mandatory in order to restore properties, which in turn require large energy consumption.

Until recently, the only published investigation on the effect of forming (tensile strain) and post forming heat treatments on steel properties was an old study by Bunk⁽⁵⁾, which had examined pressure vessel steels that are far different from the steels being considered for the offshore structures.

In a recent two year program, a systematic study on cold formability of steel plates was carried out at the Research and Development Centre of AMCA International in Lachine with IRAP support^(6,7,8). For the twelve steels investigated, maximum strain levels in the range 7 to 9.5% were achieved. As expected, yield and ultimate tensile strengths increased with forming strain, and simultaneously, the CVN toughness deteriorated, (absorbed energy values decreased and transition temperature increased). Stress relieving subsequent to forming substantially restored the CVN toughness except for micro-alloyed steels such as ASTM A633 Gr C or E (normal sulphur levels). Strain ageing invariably had an adverse effect on CVN toughness of steels, including ASTM A710 Gr A Cl 3 steel.

In spite of the rather large scope of this project, it did not deal with two important aspects - the effect of stress relief in countering the strain age embrittlement and toughness assessment using valid fracture toughness tests (such as crack tip opening displacement [CTOD] test) ⁽⁹⁾ to evaluate the suitability of cold formed plates at low design temperatures.

The two steels chosen for this investigation are believed to be potential candidates for offshore structural applications, and are: (i) a special heat melted by Algoma Steel Corporation to Lloyds LT60 specification and meeting CSA G40.21 Gr 350 WT requirements as well. It was designed with Canadian offshore and Arctic vessel applications in mind and (ii) ASTM A710 Gr A Cl 3 steel which also

was specifically developed for use in the Arctic region. A710 Gr A Cl 3 steel is a quenched and precipitation hardened high strength steel whereas LT60 steel is a normalized microalloyed steel.

The scope of the present study is to undertake a laboratory investigation to examine the suitability of the above two steels, for use in the construction of offshore structures and Arctic vessels, by assessing the deterioration in toughness at the tension surface of cold roll-formed plates that may be subsequently subjected to strain ageing and/or stress-relieving thermal cycles.

2. EXPERIMENTAL PROCEDURE

2.1 Materials:

The two steels viz. LT60 (Steel No. 1) and A710 Gr A Cl 3 (Steel No. 2) were procured in the form of 63mm thick plates with the longer side parallel to the rolling direction. LT60 steel was received in the normalized form whereas A710 Gr A Cl 3 was received in the quenched and aged condition. The latter steel had been austenitized at 900°C for 150 minutes, water quenched and precipitation hardened at 595°C for 30 minutes and air cooled. The chemical composition for both the steels as analyzed by Technitrol Canada Ltd., are given in Table 1.

2.2 Cold Bending:

Bending was performed on a Wilhelmsburger three-roll forming machine (Model DWVH 3660/120). The machine has a power requirement of 150 h.p. and is designed for bending plates with maximum width of 3660 mm. Minimum inside diameter obtained using this pyramid type machine was 1015mm.

For both the steels, 610 X 2440mm size plates with 2440mm side parallel to the rolling direction were used for bending. The following rolling procedure was used (Fig. 1) for each steel.

A 610 X 410mm plate was cut for testing the as-received or 0% strain (XA) condition, where X is the steel number.

A portion of the remaining plate was roll-formed to the lower of the two outer fibre strain levels planned (XB) viz. approximately 3%. A 610 X 410mm section with strain B was removed by flame cutting for heat treatment and testing. The rest of the plate was roll-formed to the higher outer fibre strain level (also dictated by the roll diameter and capacity) planned (XC) which was approximately 6%. Again, a 610 X 410mm section with strain C was removed. The rolling direction was parallel to the roll-forming direction in the bending operation. One of the plates roll-formed to 5.5% outer fibre strain is shown in Figure 2.

2.3 Outer Fibre Strain

The outer fibre strain in a steel plate after roll-forming to a cylindrical shape can be calculated using the expression:

$$\text{Outer fibre strain} = \frac{R_{OD} - R_{NA}}{R_{NA}} \quad (1)$$

where, R_{OD} is the outer radius of the cylinder. $R_{NA} = (R_{OD} \times R_{ID})^{\frac{1}{2}}$ is the radius to the neutral axis and R_{ID} is the inner radius of the cylinder.

Wooden templates were used as guides to roll-form the plates to a certain radius, i.e., strain value.

The inner curvature of the steel plate was traced on a sheet of paper and the inner radius (R_{ID}) of the plate was calculated using the expression:

$$R_{ID} = \frac{(c/2)^2 + h^2}{2h} \quad (2)$$

where c is the chord length and h is the height of the curvature normal to the centre of the chord. Expressions (1) and (2) were used to calculate either the strain or the radius corresponding to a particular nominal strain in the steel plate.

2.4 Dye Penetrant Check:

The roll-formed plates were checked for cracks at the outer surface and the edges using dye penetrant examination, before sectioning. No cracks were observed in any of the roll-formed plates.

2.5 Heat Treatment

Each of the sections XA, XB and XC were divided into subsections to give approximately 100-150 X 300mm pieces as shown in Figure 1. These pieces were labelled XYR, XYS, XYE, XYES and XYEE indicating a strain of Y (= A,B or C) with R,S,E,ES and EE denoting as-roll formed (or as received), stress-relieved, strain-aged at 370°C, strain aged at 370°C plus stress-relieved and strain-aged at 250°C conditions, respectively.

The strain ageing was carried out at 370°C for the pieces labelled XYE and XYES. A thermocouple was attached to the piece and put in a furnace kept at 370°C. When the temperature in the piece reached 370°C as registered by the thermocouple, the piece was held at that temperature for 1 hour, removed from the furnace and air cooled. Similarly, the strain ageing was carried out at 250°C for one hour for the pieces labelled XYEE.

The stress-relieving was carried out in a Canadian General Electric box furnace, whose temperature could be controlled by a Honeywell Electronik 15 controller. The pieces marked XYS and XYES (after the strain-aging heat treatment) were placed in the furnace and heated to 620°C at a rate of 80°C/hour (above 427°C). The pieces were stress-relieved at $620 \pm 25^\circ\text{C}$ for 150 minutes and cooled in the furnace at a rate of 80°C/hour (up to 427°C), to room temperature.

2.6 Location of Specimens

During cold forming, the maximum tensile strain occurs at the outer surface of the plate (outer fibre strain). Consequently, the mechanical properties of interest are those at the outer surface. It was therefore decided to extract subsize Charpy V-notch and tensile specimens from locations as close to the surface as possible. The schematic location of the blanks for these specimens is shown in Figures 3 and 4.

2.7 Mechanical Testing

2.7.1 Tensile Tests

Tensile specimens 4.5mm in diameter X 25.4mm in gauge length were machined. Tensile tests were performed in a Baldwin Testing Machine. At least 2 specimens were tested at room temperature for each condition using an initial strain rate of 0.02 per minute.

2.7.2 Charpy V-Notch Impact Testing

Approximately 15 subsize Charpy specimens per condition, 10 X 7.5mm in cross-section and 55mm long, were machined with the length of the specimen parallel to the roll-forming direction. The V-notch was put in the 7.5mm side of the specimen which was normal to the outer surface of the plate. The impact tests were carried out in the temperature range -130°C to room temperature to obtain the full transition curves. The lower temperatures (<-80°C) were achieved by using a mixture of 60% of ethanol + 40% of methanol and liquid nitrogen.

Charpy impact tests were also carried out for some selected conditions (OIAR, OICR, and OICES) for LT60 steel, using subsize transverse Charpy specimens, i.e., the specimen length was perpendicular to the rolling and the roll-forming directions.

2.7.3 Crack Tip Opening Displacement (CTOD) Tests⁽⁹⁾

The CTOD value at the design temperature has been used as one of the parameters to assess the structural integrity of offshore production platforms in the North Sea. To determine the CTOD values, it would be desirable to perform the tests on the outer fibre of the formed plates. However, the geometry and size considerations make it impractical for the CTOD specimens to be extracted and tested in this manner.

Instead, specimens were prepared with equivalent tensile strains (by prestraining) so that CTOD tests could be carried out as per BS 5762. For prestraining tensile specimens 38 X 38mm in cross section and 205mm in gauge length, were used. The specimens were strained to the desired plastic strain levels equivalent to the roll-formed outer fibre strains, at an initial strain rate of 0.02/minute and unloaded as shown in Figure 5. Some of the prestrained specimens were subsequently heat-treated. The formed and heat-treated conditions were selected based upon the CVN results. These conditions are given in Table 2. For each condition, 3 subsidiary specimens, 36 X 36mm in cross-section and 180mm in length with one of the surfaces corresponding to the original plate surface (as shown in Figure 6) were machined. The notch and the fatigue pre-cracks were put on the side corresponding to the thickness side of the plate. An effective a/W ratio of ~ 0.5 was used and the CTOD tests were carried out as per BS 5762. For each condition in Table 2, one specimen was tested at -60°C . If the CTOD value was less than 0.25mm, the other two

specimens for each conditions were tested at -50°C . If the CTOD value was $> 0.25\text{mm}$, the test was carried out at -60°C for that condition. In addition, CTOD tests at -30°C were carried out for A710 Gr A Cl 3 steel roll-formed to 3% outer fibre strain. After recording the appropriate CTOD values, the specimens were cooled in liquid nitrogen and broken completely into two halves. The CTOD tests were sub-contracted out to the Welding Institute of Canada. The crack front of the fatigue precrack was examined to check the validity of the test.

2.7.4 Drop Weight Tests⁽¹⁰⁾

The drop weight test is another standard and economical test developed for assessing toughness characteristics of structural steels under dynamic loading conditions. ASTM Standard E208 describes standard specimen sizes and procedures to determine the nil ductility transition (NDT) temperature - the maximum temperature where a standard drop weight specimen breaks when tested according to the provisions of this method. Thus, this test provides a measure of fracture initiation. Also, the test is an economic and adequate substitute for the expensive crack arrest temperature (CAT) test. The NDT temperature measured by the drop weight test, defines the CAT curve in terms of a relative temperature scale, i.e. $\text{NDT} + \Delta T$. The designers can use the $\text{NDT} + \Delta T$ defined CAT curve to establish the fracture arrest temperature for stress levels of design interest.

In view of this, eight P₂ type (130 X 50 X 19mm in size) specimens were prepared for each of the as-received and stress-relieved conditions of A710 Gr A Cl 3 steel. In each specimen, the long side was parallel to the rolling direction of the plate, short side corresponds to the thickness side of the plate and the surface where the crack starter bead was deposited corresponded to the original surface of the plate. The drop weight tests were carried out at the Ontario Research Foundation.

2.8 Metallography and Fractography

The metallography was performed on the thickness side of the plates close to the outer surface of the formed pieces. Some of the etched specimens were examined in a scanning electron microscope (SEM).

A selected number of fracture surfaces from the CVN and CTOD tests were also examined in the scanning electron microscope. The region examined on the fracture surface of the CTOD specimen was the crack initiation region adjacent to the fatigue precrack tip. The SEM work was carried out at QRL Analysis Corporation.

3. RESULTS

3.1 Tensile Test Data

Tensile properties evaluated include yield strength (YS-lower yield point or 0.2% offset), ultimate tensile strength (UTS), total elongation, uniform elongation and reduction in area. These tensile properties obtained at different strain levels and the combination of strain levels and heat-treatments are given in Table 3 to 8 for both the steels.

3.2 Charpy V-Notch Impact Properties

Using impact data obtained from 10 x 7.5mm Charpy specimens, the following equations have been used to estimate the transition curves for 10 x 10mm cross-section specimens⁽¹¹⁾.

$$\begin{array}{l} \text{Energy absorbed by} \\ 10 \times 10\text{mm specimen} \end{array} = \begin{array}{l} \text{Energy absorbed by} \\ 10 \times 7.5\text{mm specimen} \end{array} \times \frac{4}{3} \quad (3)$$

$$\begin{array}{l} \text{Temperature of test for} \\ 10 \times 10\text{mm specimen, in } ^\circ\text{C,} \end{array} = \begin{array}{l} \text{Temperature of test for} \\ 10 \times 7.5\text{mm specimen in } ^\circ\text{C} \end{array} + \Delta T \quad (4)$$

$$\text{where } \Delta T = 0.9(10-W)^2 = 5.6^\circ\text{C (for } W = 7.5\text{mm)}$$

Estimated impact values (CVN) for the 10 x 10mm specimen and the corrected temperatures are given in Tables 3 to 8 for both the steels. Corresponding lateral expansion and percent shear values are also given in these tables; however, it should be noted that

no corrections were applied for the latter properties since no such correction factors have been developed in the literature. The corrected transverse Charpy V-notch impact results for LT60 steel are given in Table 9.

The impact energy transition curves were plotted for each outer fibre strain level of the steels using corrected data. These are shown in Figures 7 to 13.

3.3 CTOD Test Data

The CTOD test results such as δ_c [Crack tip opening displacement at either: (a) unstable fracture or (b) onset of arrested brittle crack or pop-in, when there is no evidence in either (a) or (b) to suggest that slow crack growth has occurred], δ_u [crack tip opening displacement at either: (a) unstable fracture or (b) onset of arrested brittle crack or pop-in, when there is evidence in either (a) or (b) to suggest that slow crack growth has occurred], and δ_m (crack opening displacement at first attainment of maximum force plateau) obtained for both the steels are given in Tables 10 to 14. Figures 14 and 15 show the fractured CTOD specimens. Except for 02CES #1, all the other tests should be valid.

3.4 NDT Temperatures

The NDT temperatures were found to be -65° and -70°C for the as-received and the stress-relieved A710 Gr A Cl 3 steel, respectively.

These values are shown in the respective Charpy impact transition curves in Figure 7.

3.5 Metallography and Fractography

The optical photomicrographs obtained for both the steels at different combinations of outer fibre strain and heat treatments are given in Figures 16 to 21. Also, some of the typical microstructures examined using a scanning electron microscope are given in Figure 22 to 25.

The grain size measurements made on Lloyds LT60 and A710 Gr A Cl 3 steels yielded average ASTM grain sizes of 8 and 10 respectively for the as-received microstructures.

The fractographs obtained for some of the selected fracture surfaces of the CVN and CTOD specimens are given in Figures 26 to 29.

4. OBSERVATIONS AND DISCUSSIONS

4.1 Tensile Properties

To evaluate the effects of outer fibre strains and the heat-treatments on YS, UTS, total and uniform elongations, these tensile properties listed in Tables 3 to 8 are plotted against the outer fibre strains in Figures 30 to 34.

4.1.1 Yield Strength (YS)

- (a) The yield strength increased with the outer fibre strain for both the steels. Increases in YS were 36 and 30.5% respectively for the steels LT60 and A710 Gr A Cl 3, over the as-received condition of the corresponding material, when roll-formed to the maximum strain possible.
- (b) For both the steels, further increase in yield strength was observed, over the as-roll-formed condition, when strain aged at 250 or 370°C following the roll-forming.
- (c) Stress-relief heat-treatment following roll-forming, and roll-forming plus strain ageing decreased the YS values lower than those of the respective as-formed condition for both the steels. In the case of A710 Gr A Cl 3 steel, the stress relief heat-treatment restored the YS values of the as-roll-formed, and roll-formed plus strain aged steel to that of the as-received steel.

- (d) Each heat treatment given to the as-received LT60 steel, increased its YS value. However, most of the heat treatments given to the as-received A710 Gr A Cl 3 steel reduced the YS of the material.

4.1.2 UTS

- (a) The UTS value increased for LT60 steel as the outer fibre strain increased. However, the increase was small; 6.5% at 6% strain. For A710 Gr A Cl 3 steel, the outer fibre strain did not seem to affect the UTS value of the as-received material.
- (b) Heat treatments following the roll-forming of LT60 steel further increased the UTS value compared to the respective as-roll-formed condition. Roll-formed A710 Gr A Cl 3 steel showed increase in UTS value, when strain aged. The stress-relieving of the as-received, roll-formed and the roll-formed plus strain-aged A710 Gr A Cl 3 steels, decreased its UTS value.

4.1.3 Total and Uniform Elongations

- (a) The total and uniform elongations decrease with the outer fibre strain for both the steels.
- (b) The total elongation, a measure of ductility, decreased as a result of the strain ageing treatment for both the steels.

In the case of LT60 steel, strain-ageing at 250°C decreased the total elongation by a greater amount than when strain aged at 370°C.

- (c) Stress-relieving treatment seemed to improve the total and uniform elongation in both the steels. The effect was small for LT60 steel whereas complete restoration of the elongation values to that of the as-received material was possible by stress-relieving alone for A710 Gr A Cl 3 steel.
- (d) The uniform elongation of a steel is indicative of the maximum outer fibre strain to which the steel can be roll-formed without cracking at the tension surface (provided machine has adequate capacity). In a previous report, it was shown that the uniform elongation of the steel could be related to the roll-forming strain as follows:

$$\begin{array}{lcl} \text{uniform elongation} & & \text{uniform elongation} \\ \text{of the as-received} & = & \text{of the roll-formed} \\ \text{steel, \%} & & \text{steel, \%} \end{array} \quad \begin{array}{l} \text{outer fibre strain} \\ \text{of the roll-formed} \\ \text{steel, \%} \end{array} \quad + \quad \begin{array}{l} \text{uniform elongation} \\ \text{of the roll-formed} \\ \text{steel, \%} \end{array} \quad (5)$$

This equation clearly shows that there is greater ductility left in LT60 steel (15.5%) than in A710 Gr A Cl 3 steel (2.1%) and hence, the former can be roll-formed to much higher outer fibre strain levels (smaller diameter) without cracking. Such smaller diameter, cylindrical shapes could be formed for the present A710 Gr A Cl 3 steel by providing an intermediate stress-relief heat-treatment.

4.2 Impact Properties

Only the impact energy data was analyzed. No attempt was made to analyze the lateral expansion and the percent shear data since no correction factors were available to convert these subsize specimen data to the standard data.

4.2.1 Charpy Impact Energy Transition Curves

(i) LT60 Steel:

- (a) The transition curves moved to the right (higher temperatures) as the outer fibre strain increased (refer to Figures 7 to 9) indicating the deterioration in transition temperatures.
- (b) The effect of strain-ageing was also to shift the transition curves to the right in both the as-received and the roll-formed conditions. Strain-ageing at 250°C had a greater effect on the shift than ageing at 370°C. Stress-relieving after strain-ageing essentially shifted the transition curves of the strain-aged material to further right. This showed that stress-relieving could not improve the deterioration in toughness caused by strain ageing in the transition region for this steel.
- (c) Stress-relieving of the as-received and the roll-formed steels shifted the transition curves to the right. This showed that stress-relieving had a detrimental effect on the toughness of LT60 steel.

- (d) The impact energy absorbed at -60°C for the as-received steel was 193J. Even after the various heat treatments, the minimum impact energy value observed in the as-received steel was 192 J at -60°C . The steel with an outer fibre strain of 6% showed CVN value of 140 J at -60°C and the lowest value after heat-treatments was 86 J. To the extent that CVN impact energy is indicative of the adequacy of the steel, the observed values indicate this steel to be suitable for Canadian offshore structures and Arctic vessels where the ambient temperatures could be as low as -60°C .
- (e) The CVN values obtained from the transverse specimens were lower than those of the respective longitudinal specimens. That is as expected. Only a limited amount of data is available; however, these data show 62J CVN values at -60°C at an outer fibre strain level of 6%. The stress-relieving decreased this CVN value to about 18 J (refer to Fig. 10). The 27J transition temperature is still -55°C .
- (ii) A710 Gr A Cl 3 Steel
- (a) The transition curves shifted to the right as the outer fibre strain increased. (Refer to Figures 11 to 13).

- (b) The effect of strain-ageing was to shift the curves to the left. Except for the as-received steel, the effect was small on the roll-formed steel. This behaviour and the changes in tensile properties observed due to strain ageing indicate that there could be two simultaneous competing processes occurring in the steel viz. (i) continued overageing, and thus improvement in toughness, and (ii) strain-ageing trying to deteriorate the ductility and toughness of the steel.
- (c) Stress-relief heat treatment on the as-received, roll-formed and strain-aged steel shifted the respective transition curves to the left. The lowering of the transition temperature due to stress-relieving was very significant. This indicated that stress-relief heat treatment was beneficial in improving the CVN values for A710 Gr A Cl 3 steel.
- (d) The CVN value was 146 J at -60°C for the as-received steel. This value decreased to 18 J when roll-formed to 5.5% outer fibre strain. In both cases, the CVN values could be improved to 180J by stress-relief heat treatments. This suggests that from formability point of view, this steel would need to be stress-relieved for extreme combinations of forming strain and design temperature.

4.2.2 CVN Impact Energy Values at -60° and -30°C

- (a) The CVN values at -60°C decreased with the outer fibre strain for both the steels. Decrease in CVN values of 29 and 88% from those of as-received conditions, were seen at the maximum outer fibre strains for LT60 and A710 Gr A Cl 3 steel, respectively. (Refer to Figures 35 and 37.)
- (b) The CVN values at -30°C decreased with the increase in outer fibre strain for A710 Gr A Cl 3 steel whereas for LT60 steel, the CVN values remained unaltered with the increase in the outer fibre strain. (Refer to Figure 36 and 38.)
- (c) For LT60 steel, the effect of heat treatment at the maximum outer fibre strain was to decrease the CVN values both at -60° and -30°. Heat treating the as-received and the roll-formed A710 Gr A Cl 3 steel increased the CVN values both at -60° and -30°C. However, in a previous study^(6,7) it was observed (refer to Figures 39 and 40) that the effect of strain-ageing was to lower the CVN values of the as-received and roll-formed A710 Gr A Cl 3 steel (76mm thick plate). Even though this is contrary to the present findings, it is not surprising. The mill reports indicate that the quench and precipitation hardening treatments given to these two A710 Gr A Cl 3 steels were different. The A710 Gr A Cl 3 steel used in the present investigation was austenitized at 900°C for 150 minutes, water quenched, precipitation hardened at 595°C for 30 minutes and air-cooled.

The steel used in the previous study was austenitized at 900°C for 270 minutes, water quenched, precipitation hardened at 650°C for 30 minutes and air-cooled. Studies⁽¹²⁻¹⁹⁾ have shown that the austenitizing temperature, austenitizing duration, precipitation hardening temperature and the duration of the precipitation hardening treatment affect the mechanical properties of A710 Gr A Cl 3 steel significantly. This suggests that the A710 Gr A Cl 3 used in the present investigation may not have undergone an adequate precipitation hardening treatment to give optimum level of mechanical properties. That may be why the strain-ageing treatment increased the CVN values of the as-received and the roll-formed A710 Gr A Cl 3 steels.

4.3 Nil Ductility Transition Temperature

The NDT temperatures for the as-received and the stress-relieved A710 Gr A Cl 3 steel are marked in the respective CVN transition curves in Figure 11. The NDT temperatures are higher than the brittle transition curves. This is not surprising since CVN values give the total energy for initiation and propagation of the fracture under dynamic loading condition. The NDT temperature only characterizes the dynamic initiation of the fracture. A higher NDT temperature than the brittle transition shown by the CVN curve indicates that the dynamic initiation energy is significantly lower than the propagation energy. This implies that A710 Gr A Cl 3 steel may have better resistance to the propagation of the fracture (crack arrest) than the initiation of the fracture.

4.4 CTOD Values

The criterion generally stipulated by the end users of offshore structures in the North Sea oil industry for critical welded joints, for example, in the splash zone has been a minimum CTOD value of 0.1 to 0.25mm at -10°C from 2B X B specimens⁽²⁰⁾. There is, also, usually an accompanying CVN absorbed energy requirement. Similar CTOD and CVN toughness requirements may also be demanded for the Canadian offshore structures and Arctic vessels.

In the present investigation, the CTOD values measured for LT60 and A710 Gr A CI 3 steels (refer to Tables 10 to 14) show that:

- (a) For LT60 steel increase in tensile strain did not seem to have any effect on the CTOD values at -60°C . However, the stress-relief, strain age and strain age + stress-relief heat treatment following 6% tensile strain lowered the CTOD values of the as-strained steel.
- (b) The CTOD values at -60 or -50°C decreased with the increase in tensile strain for A710 Gr A CI 3 steel. The effect of strain ageing at 250°C following 5.5% tensile strain was to further deteriorate the CTOD values of the as-strained steel. Stress-relieving generally increased the CTOD values of the strained and strained + aged A710 Gr A CI 3 steel; however, there was a greater variation in results in that one specimen for each condition exhibited brittle behaviour, and thus low CTOD value - 0.038mm.

(c) For LT60 steel, CTOD values $>0.25\text{mm}$ could be achieved at -60°C under all conditions of outer fibre strain and heat-treatments used. However, such CTOD values could only be achieved in the as-received condition or by stress-relieving the as-received, roll-formed and roll-formed and strain-aged A710 Gr A Cl 3 steel. The CTOD values approached 0.25mm when the A710 Gr A Cl 3 steel with a 3% tensile strain was tested at -30°C .

(d) Using the CTOD design curve approach⁽²⁴⁾, allowable defect sizes can be calculated from the CTOD values obtained, using the following equations:

$$\bar{a}_{\max} = \frac{\delta E}{2\pi \sigma_y (\sigma_{\text{app}}/\sigma_y)^2} \quad \text{for } \frac{\sigma_{\text{app}}}{\sigma_y} < 0.5 \quad (6)$$

$$\text{and } \bar{a}_{\max} = \frac{\delta E}{2\pi \sigma_y (\sigma_{\text{app}}/\sigma_y - 0.25)} \quad \text{for } \frac{\sigma_{\text{app}}}{\sigma_y} > 0.5 \quad (7)$$

Here, σ_y is the yield stress, E is the Young's modulus of elasticity and σ_{app} is the total stress at the defect location (without the defect present) and is given by:

$$\sigma_{\text{app}} = (\sigma_{\text{design stress}} \times \text{stress corr. factor}) + \text{residual stress (from welding)}$$

For the two steels investigated, the lowest average CTOD value is obtained in the roll-formed + strain-aged (at 250°C) condition (CEE). At such locations in real structures, the residual stresses can be assumed to be zero, and the stress concentration factor to be 1. Further, assuming the design stress

to be $0.6 \times$ min. specified yield strength of the parent material, the allowable defect size at -60°C is estimated to be 102mm for the LT60 steel.

In contrast, with the same assumptions, the allowable defect size for A710 steel is 4.9mm. In the stress-relieved condition, the defect size could then be as low as 7.7mm (CTOD = 0.038mm), but is likely to be greater than 38mm (CTOD = .178mm). Similarly, for the A710 steel rolled to about 3% strain, the allowable defect size at -30°C can be estimated to be about 57mm.

It should be noted that (i) the allowable defect size is the equivalent depth of a surface-breaking crack or half the length of a buried crack as in standard LEFM solutions, (ii) based on large scale wide plate tests, the allowable or tolerable defect size is smaller than the critical size for brittle fracture by a factor of about 3.

- (e) The CVN values for both the steels at -60° or -50°C were correlated with the CTOD values in Figure 41. In this figure for the same CVN values A710 Gr A Cl 3 steel showed lower CTOD values than LT60 steel. This may be due to lower resistance of the A710 Gr A Cl 3 steel to fracture initiation. It may have higher resistance to fracture propagation under static loading conditions and this needs to be explored.

Jolley et al⁽²¹⁾ measured the CTOD and CVN values on standard Charpy size specimens for Ni-Cr-Mo(V) (2.46% Ni), Q2(N) (3.12% Ni) and HY130 (4.81% Ni) steels. The CTOD and CVN values obtained from the transition curves of these steels are plotted in Figure 41. These nickel bearing high strength heat-treated steels also gave lower CTOD values compared to the LT60 steel. These values were obtained using Charpy size specimens and, hence, a larger size specimen would have⁽²²⁾ yielded still lower CTOD values.

Baumgardt et al⁽²³⁾ measured CVN and CTOD values for St. E 355 modified (C-Mn-Nb) normalized steel (36mm thick). The CTOD and CVN values at -60°C are plotted in Figure 41. Again, there may be a specimen size effect involved in this case, since a B X 2B type of specimen was used. In any case, it can be inferred that the nickel bearing heat treated higher strength steels give lower CTOD values than the normalized C-Mn-Nb steels.

4.5 Microstructures

The LT60 had a normalized ferrite-pearlite microstructure as shown in Figures 16 to 18. No change in structure due to roll-forming or heat treatments are seen near the outer surface of the steel plates when examined in an optical microscope. The scanning electron micrographs, however, showed some effects of heat treatments as shown in Figures 22 and 23. The strain-aged specimens contained fine dispersion of second phase particles at the grain interiors (Figures 22c, e and

23c,e). Stress-relief heat-treatment seems to coarsen these second phase particles by reducing the number of particles (Figures 22 b, d and 23 b, d).

A710 Gr A Cl 3 steel had a quenched and precipitation hardened microstructure: ferrite, tempered bainite and the precipitates of a copper rich phase at the grain interiors and the boundaries. Optical microscope examination did not reveal any changes due to forming, strain-ageing, and stress-relieving treatments (refer to Figures 19 to 21). When the microstructures were examined in a scanning electron microscope, fine dispersion of the precipitates were quite evident (refer to Figures 24 and 25). Both strain-ageing and stress-relieving treatments seem to coarsen these precipitates. The coarsening of the precipitates may be partly responsible for the improvement (increase) in the CVN impact energy observed following strain-ageing and stress-relief heat treatments.

4.6 Fractographs

4.6.1 Fracture Surface of the CVN Specimens

The specimen broken at the lower shelf temperatures showed only the cleavage facets in both the steels. There is no indication of any intergranular fracture (refer to Figures 26 and 27).

4.6.2 Fracture Surface of the CTOD Specimens

The fracture initiation regions of some typical CTOD specimens are shown in Figures 28 and 29. Figure 28a and b show the fracture

initiation region of the CTOD specimens for LT60 steel which gave CTOD values of 1.285 and 1.4mm respectively. These surfaces show ductile fracture dimples. The fracture initiation region of the specimen which gave a CTOD value of 0.277mm showed a mixture of ductile fracture dimples and cleavage fracture (refer to Figure 28 c and d). The specimens which gave CTOD values of <0.25 mm, i.e. 0.18 and 0.14mm, showed essentially cleavage fracture (see Figure 28 e and f). Only a small area of ductile fracture dimples were present as shown in Figure 28e. This indicated that a CTOD value of 0.25mm acted as a critical value above which ductile fracture initiation occurred in normalized microalloyed C-Mn steels. However, this was not the case in quenched and precipitation hardened A710 Gr A Cl 3 steel. A710 Gr A Cl 3 steel which gave a CTOD value of 0.178mm showed ductile fracture dimples in the initiation region of the fracture surface as shown in Figure 29. Thus, if the design criterion were related to ductile initiation in the CTOD tests, then lower CTOD value could be specified for the precipitation and hardened steel.

5. SUMMARY AND CONCLUSIONS

1. Approximately 30-35% increase in yield strength was observed in both the steels roll-formed to ~5.5-6% outer fibre strain. Strain-ageing and stress-relief heat treatments further increase and decrease the yield strength values of both the roll-formed steels, respectively.
2. The effect of outer fibre strain on the UTS was small for both the steels. A 6.5% increase in UTS was achieved when the LT60 steel was roll-formed to 6% strain and the effect of the heat treatments were to further increase the UTS values. However, in the case of A710 Gr A Cl 3 steels, the effect of the heat treatments was to reduce the UTS at all outer fibre strain levels.
3. The total and uniform elongations decreased with the increase in outer fibre strain for both the steels. The total elongation, which is a measure of ductility, decreased further with the strain-ageing treatment in both the steels. Stress-relieving, which improved the uniform and the total elongations in both the steels, completely restored the elongation values to that of the as-received condition in A710 Gr A Cl 3 steel.
4. The uniform elongation which is a measure of the maximum outer fibre strain that can be achieved in a steel showed that LT60 steel could be roll formed to smaller diameter cylinders without

fracture giving rise to higher than 6% outer fibre strain. To accomplish this in A710 Gr A Cl 3 steel, an intermediate stress-relief heat treatment may be necessary.

5. The CVN impact energy transition curves shifted to the higher temperatures as the outer fibre strain increased in both the steels. Both strain-ageing and stress-relieving heat treatments shifted the transition curves to higher temperatures for LT60 steel but had beneficial effect (shift to lower temperatures) A710 Gr A Cl 3 steel. This was observed for both as-received and roll-formed conditions. The beneficial effect of strain ageing observed in A710 Gr A Cl 3 steel could have been due to two competing processes occurring simultaneously viz (i) over-ageing to achieve optimum properties and (ii) strain ageing trying to degrade the impact properties.
6. Stress-relieving following strain-ageing shifted the transition curves to higher and lower temperatures indicating deleterious and beneficial effects for LT60 and A710 Gr A Cl 3 steels, respectively.
7. Strain-ageing at 250°C had a greater effect on the shift than ageing at 370°C.
8. The LT60 steel with an outer fibre strain of 6% showed CVN value of 140J at -60°C. The lowest energy absorbed value at -60°C for

LT60 was 86 J after strain-ageing + stress-relieving heat treatment. A710 Gr A Cl 3 steel with an outer fibre strain of 5.5% yielded a CVN value of 18J at -60°C but this could be improved to 180J by stress-relief heat treatment alone. These adequate CVN values at -60°C observed in the as-roll-formed LT60 as well as roll-formed and stress-relieved A710 Gr A Cl 3 steels having formed strain levels of < 5.5-6%, should make them suitable for the tubulars in Canadian offshore structures which are subjected to the ambient temperatures in the range of -30° to -60°C.

A710 Gr A Cl 3 steel gave CVN value of 118J at -30°C when roll-formed to 5.5% outer fibre strain suggesting that this steel can be used in the as-formed condition at temperatures >-30°C.

9. The NDT temperatures measured revealed that the initiation energy may be lower than the propagation energy for dynamic fracture in A710 Gr A Cl 3 steel.
10. The CTOD values >0.25mm were obtained in LT60 steel at -60°C under all conditions of tensile strain and heat-treatments used. Adequate CTOD values could only be achieved in the as-received condition or by stress-relieving the as-received, strain and strained + stress-relieved A710 Gr A Cl 3 steel.

The CTOD values approached 0.25mm when the A710 Gr A Cl 3 steel with a 3% tensile strain tested at -30°C.

11. With certain assumptions, the allowable defect size at -60°C is estimated to be greater than 100mm for LT60 steel.

For the A710 Gr A Cl 3 steel, the allowable defect size could be as low as 5mm (in the formed + aged condition) under the same assumptions. As a result of stress relief, the allowable defect size is likely to increase by a factor of more than 10.

At -30°C, the allowable defect size for A710 Gr A Cl 3 steel with approximately 3% strain is estimated to be about 38mm.

12. Based on CVN results from roll-formed A710 Gr A Cl 3 steel in a previous study, it is suggested that the steel plate used had not been heat treated to maximize toughness properties. Improved performance (less severe degradation in toughness with strain) is possible with due care in selecting heat treatment temperatures and times.
13. For the same CVN values at -60 or -50°C lower CTOD values (at -60 or -50°C) were obtained for A710 Gr A Cl 3 steel compared to LT60 steel. It may be speculated that A710 Gr A Cl 3 steel has lower resistance to fracture initiation compared to LT60 steel.

14. The fracture initiation regions of the CTOD specimens of LT60 steel showed mainly cleavage fracture when the CTOD values were below 0.25mm. However, ductile fracture dimples were observed in the initiation region for A710 Gr A Cl 2 steel which showed CTOD values less than 0.25mm.

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REFERENCES

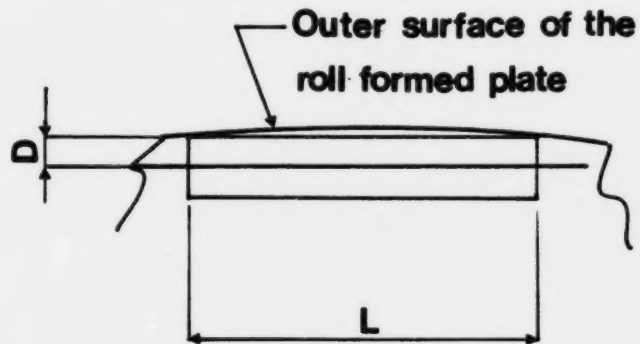
1. "A Review of Steel Properties at Low Temperatures." Prepared for Transportation Development Centre, Transport Canada, Dec. 1980. Lloyds Register of Shipping.
2. Keeler, T. "Innershield Welding." Part 1: Development and Applications, Met. Const. Nov./81, pp. 667-673, Part 2: Properties, Met. Const. Dec./81, pp. 750-753.
3. Harrison, J.D. "Material Selection Considerations for Offshore Steel Structures." Weld. Inst. Res. Report 150/1981, July/81.
4. Eide, G.H. et al. "Review of Steels Used in the Construction of Offshore Structures." Technical Report submitted by DNV to EMR, Canmet.
5. Bunk, A.P., WRC Bulletin 158. "Fabrication and Environmental Considerations." PVRC Interpretive Report of Pressure Vessel Research, Sect. 3, Jan./71.
6. Bala, S.R. "Cold Formability of Steel Plates." DB/AMCA Report No. 1-R78-019/4, Vol. 1 & 2, May/81.
7. Bala, S.R. and Malik, L. "Cold Formability of Steel Plates." Welding and Metal Fabrication, 1983/March, Vol. 51, No. 2, pp. 199-108,
8. Tyson, W.R. and Bala, S.R. "Dynamic Toughness and Cold Formability of Steel Plate." Presented in the Sixth Canadian Symposium on Engineering Applications of Mechanics to Energy Resource Industries, June 7 & 8, 1982.
9. BS 5762: 1979. "Methods for Crack Opening Displacement Testing." The British Standards Institution.
10. ASTM Designation: E208-81. "Standard Methods for Conducting Drop Weight Test to Determine Nil Ductility Transition Temperature of Ferritic Steels." 1983 Annual Book of ASTM Standards, Section 3, Vol. 03.01.
11. Towers, O.L. "Charpy Requirements for Sub-Size Specimens." The Welding Institute Research Bulletin, Vol. 19, 1978, pp. 224-227, (available to WI members only).
12. Jesseman R.J. and Murphy G.J. "High Strength Precipitation Hardened Alloy Steel for Heavy Section Applications." Paper presented at the 1977 Triple Engineering Conference, Oct. 28-72, 1977, Chicago, ASM.

13. Jesseman, R.J. and Smith, R.C., 1975. "Effects of Straining, Ageing and Stress-Relieving on Mechanical Properties of Steels for Arctic Service." Transactions of the ASME Journal of Engineering for Industry 97(2): pp. 408-416.
14. LeMay, I., Krishnadev, M.R., and Galibois, A. "Current and Potential Steels for Far North Pipelines." Pipeline Industry, 41 (1974) pp. 46-50.
15. Jesseman, R.J. and Murphy, G.J. "Mechanical Properties and Precipitation Hardening Response in Armco NI-CoP (ASTM A710 Gr A and A736) Alloy Steel." Paper presented at the International Conference on Copper in Steel held on May 25-27, 1983, in Luxembourg.
16. "Chemical Composition and Mechanical Property Data for ASTM A710 Gr A Alloy Plates." Compiled by Armco Inc., May, 1981.
17. Murphy, G.J. and Jesseman R.J. "Mechanical Properties and Precipitation Hardening Response in ASTM A710 Grade A and A736 Alloy Steel Plates." Presented at the International Conference on Technology and Applications of High Strength Low Alloy Steels." Philadelphia, October 3-6, 1983.
18. Hicho, G.E., Fields, R.J. and Singhal S. "Effect of Thermal Processing Variations on the Mechanical Properties and Microstructure of a Precipitation Hardening HSLA Steel." *ibid.*
19. Miglin, M.T., Hirth, J.P. and Rosenfield A.R. "Effects of Microstructure on Fracture Toughness of a High-Strength Low-Alloy Steel." *Met. Trans/ A*, 1983 Oct., Vol. 14A, pp. 2055-2061.
20. Taylor, D.S. and Evans, G.M. "Systematic Development of a New Range of MMA Electrodes for Critical Areas of Offshore Fabrication." Paper 29, Proceedings of the Second International Conference on Offshore Welded Structures, The WI, London, 1982, Nov. 16-18, pp. P29-1 P29-13.
21. Jolley, G., Kilpatrick, I.M. and Main, R. "Effect of Notch Activity on the Fracture Toughness of Three Low Alloy High Yield Strength Steels." *Welding J. Res. Suppl.*, 1973 Dec., Vol 52, pp. 543s-548s.
22. Lereim, J. "Elastic-Plastic Fracture Analysis of Heavy Walled Structural Elements", Paper 13, Proceedings of the Second International Conference on Offshore Welded Structures, The WI, London, 1982 Nov. 16-18, pp. 13-1 to P13-10.
23. Baumgardt, H. "Special Features in the Development of High Strength Steels for Offshore Technology." Paper 46, *ibid.*, pp. P46-1 to P46-9.

24. Smith, I.J. et al. "A Defect Assessment Method Using Finite Elements and the CTOD Design Curve, for Use in the Design of Offshore Welded Structures." Paper 21, 2nd International Conference on Offshore Welded Structures, London, November, 1982.

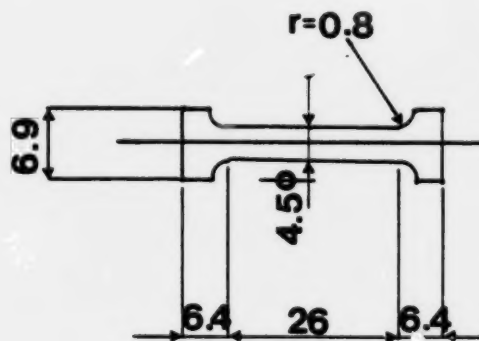


Figure 2: A710 Gr A Cl 3 Steel showing a portion of the plate roll-formed to 5.5% outer fibre strain.



D = 4 mm for TENSILE SPECIMENS
= 5 mm for CHARPY SPECIMENS

Figure 3: Location of Tensile and Charpy Specimens.



All dimensions in mm

Figure 4: Dimensions of the Tensile Specimens.

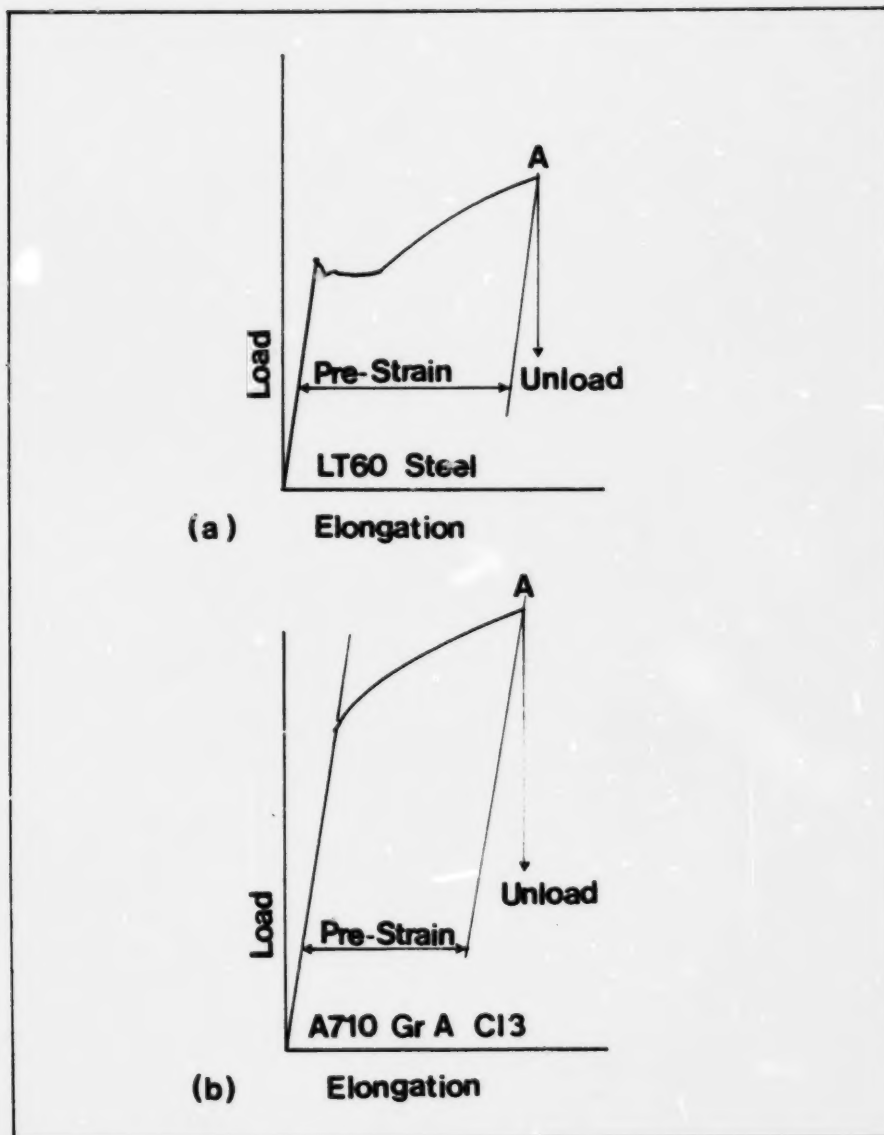


Figure 5: Load Elongation Curves for the Candidate Steels
Pre-Strained to Point A,
a) LT60 Steel and b) A710 Gr. A Cl 3.

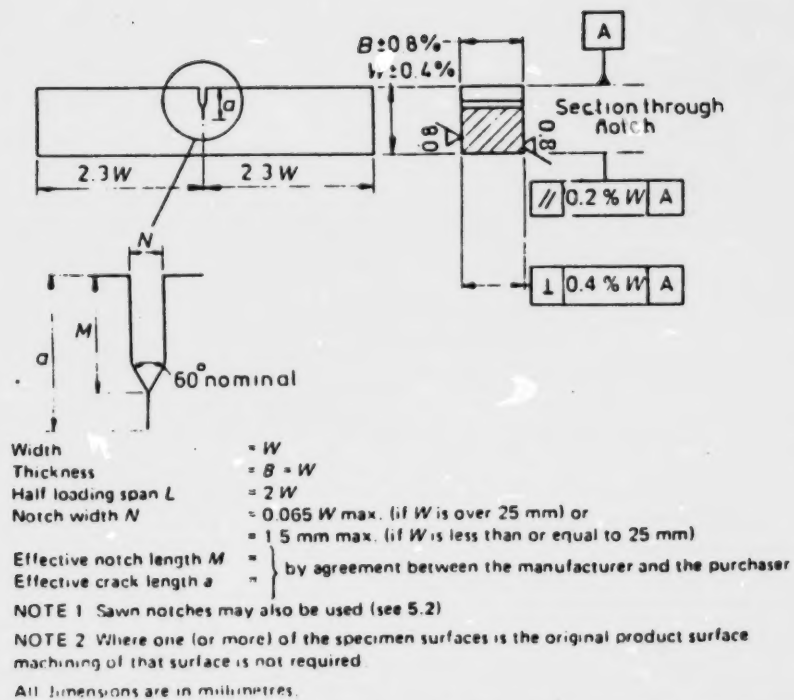


Figure 6: Proportional dimensions and tolerances for bend test pieces: subsidiary test piece

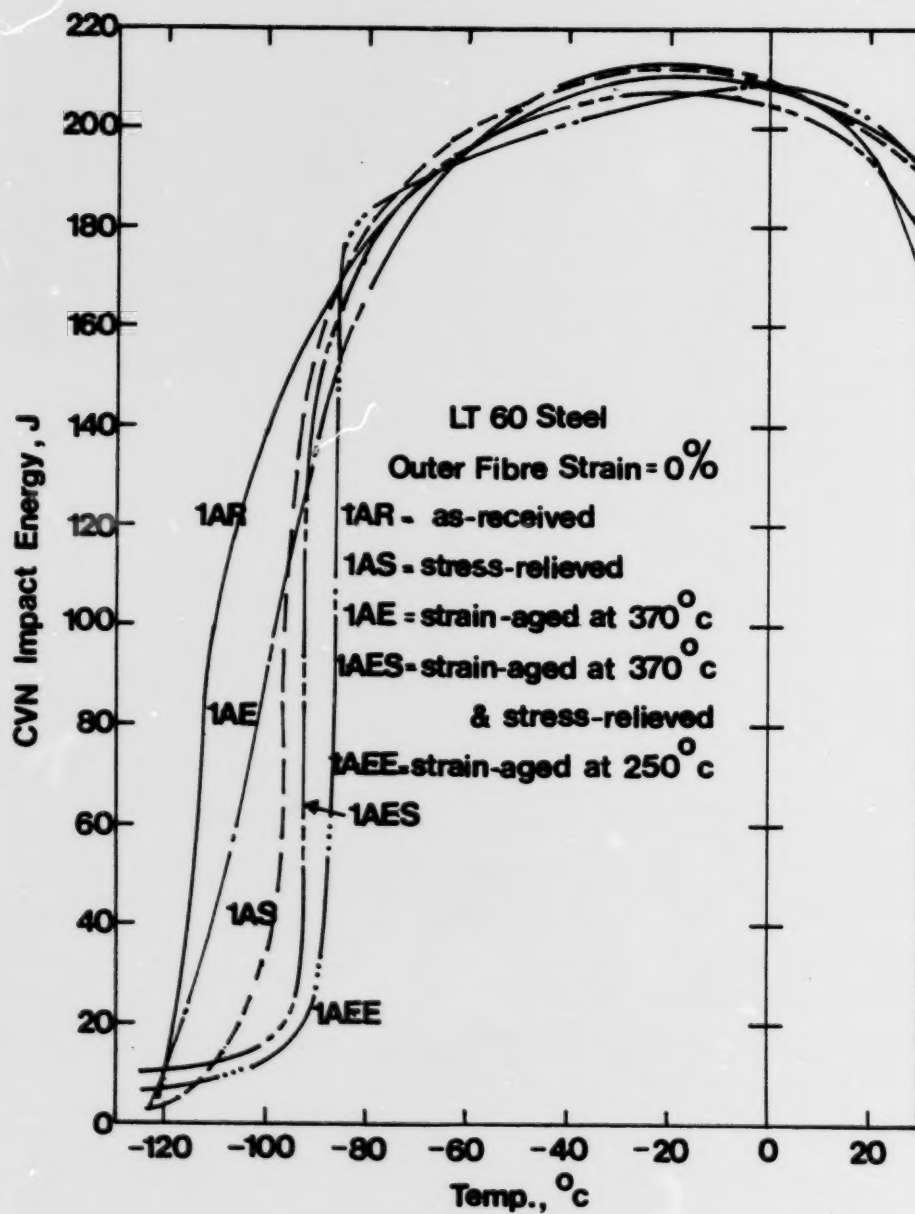


Figure 7: Impact Energy Transition Curves for As-Received LT60 Steel.

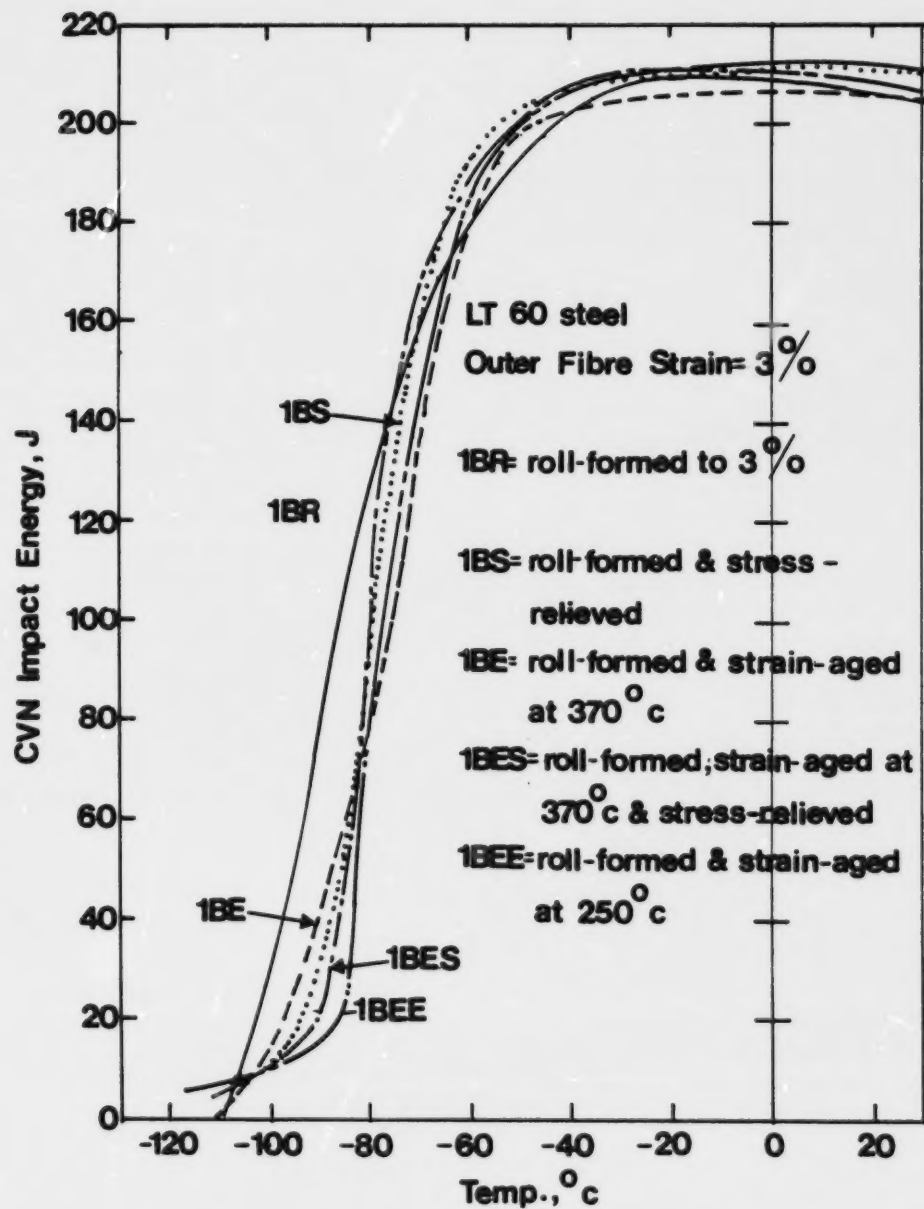


Figure 8: Impact energy transition curves for roll-formed LT60 steel with 3% outer fibre strain.

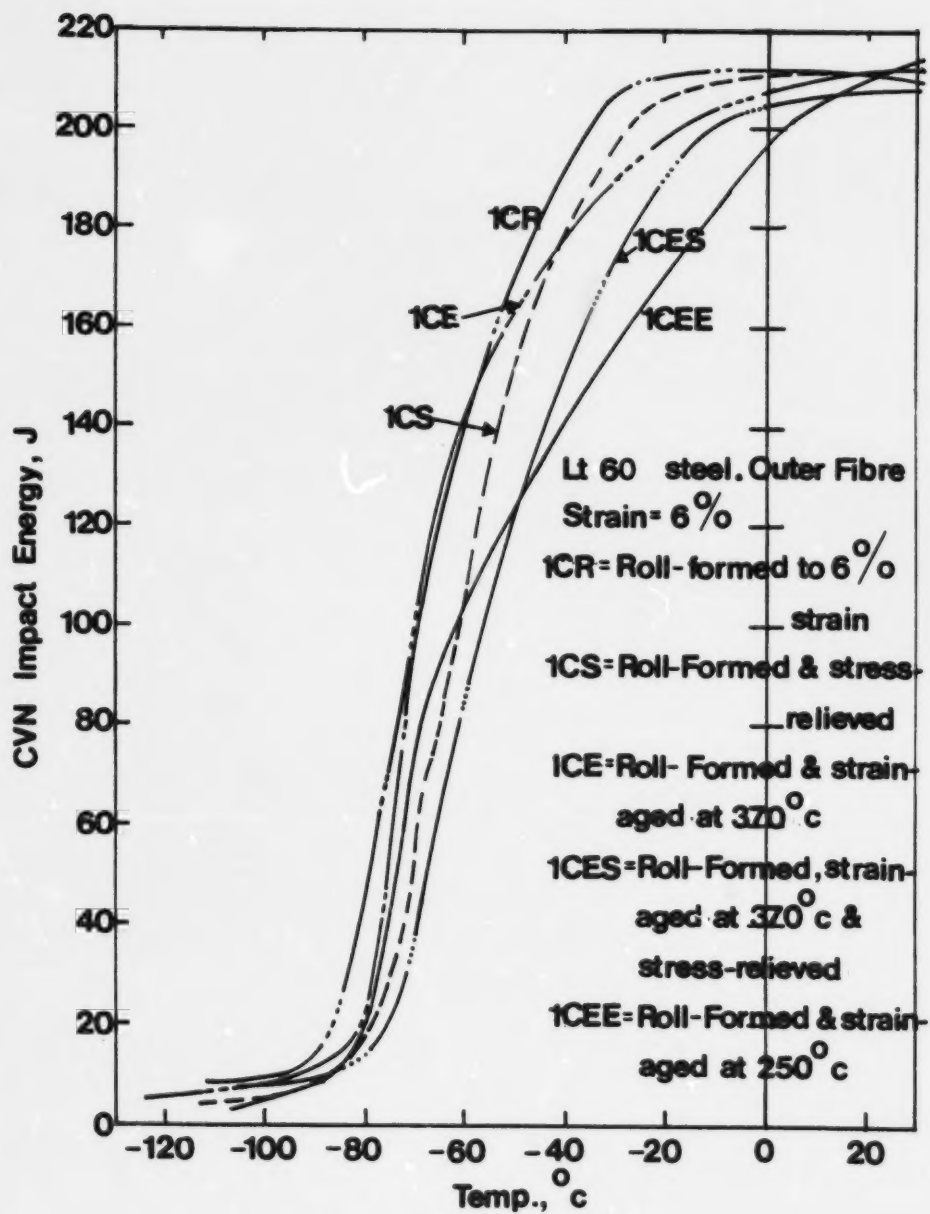


Figure 9: Impact energy transition curves for roll-formed LT60 steel with 6% outer fibre strain.

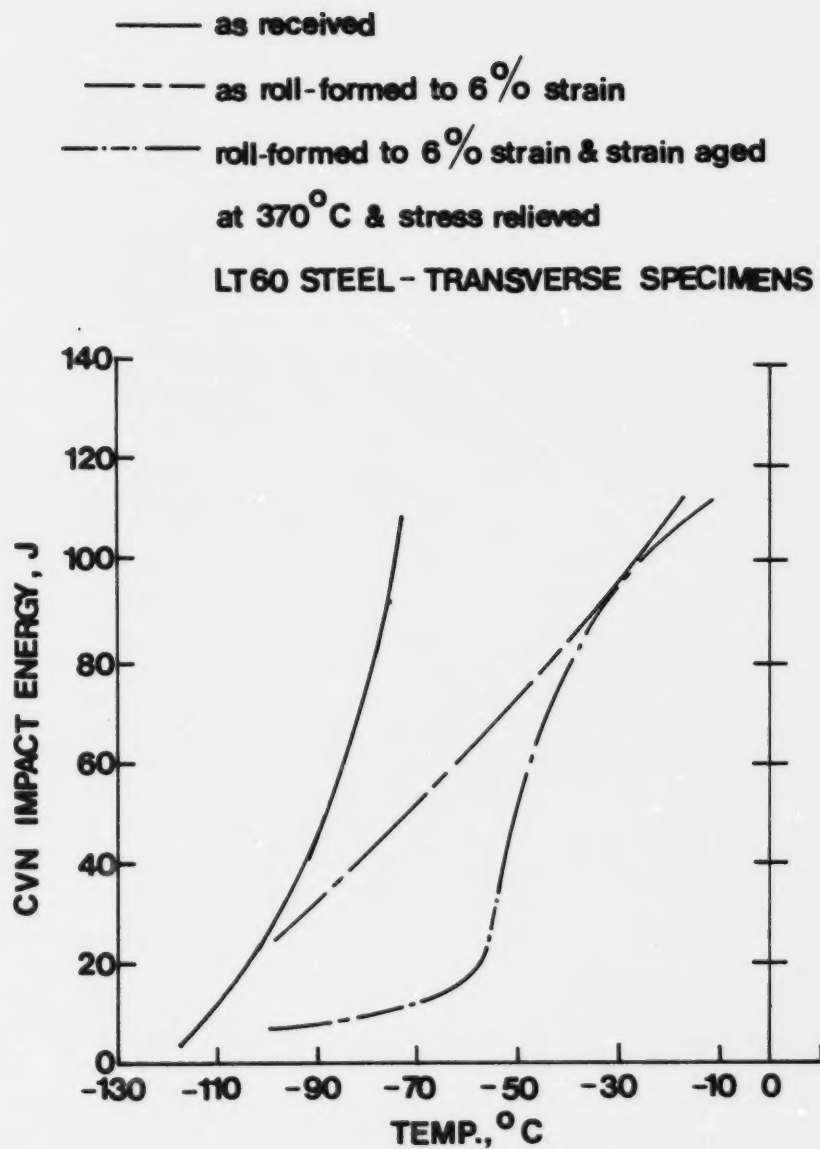


Figure 10: Impact energy transition curves for transverse specimens of LT60 steel.

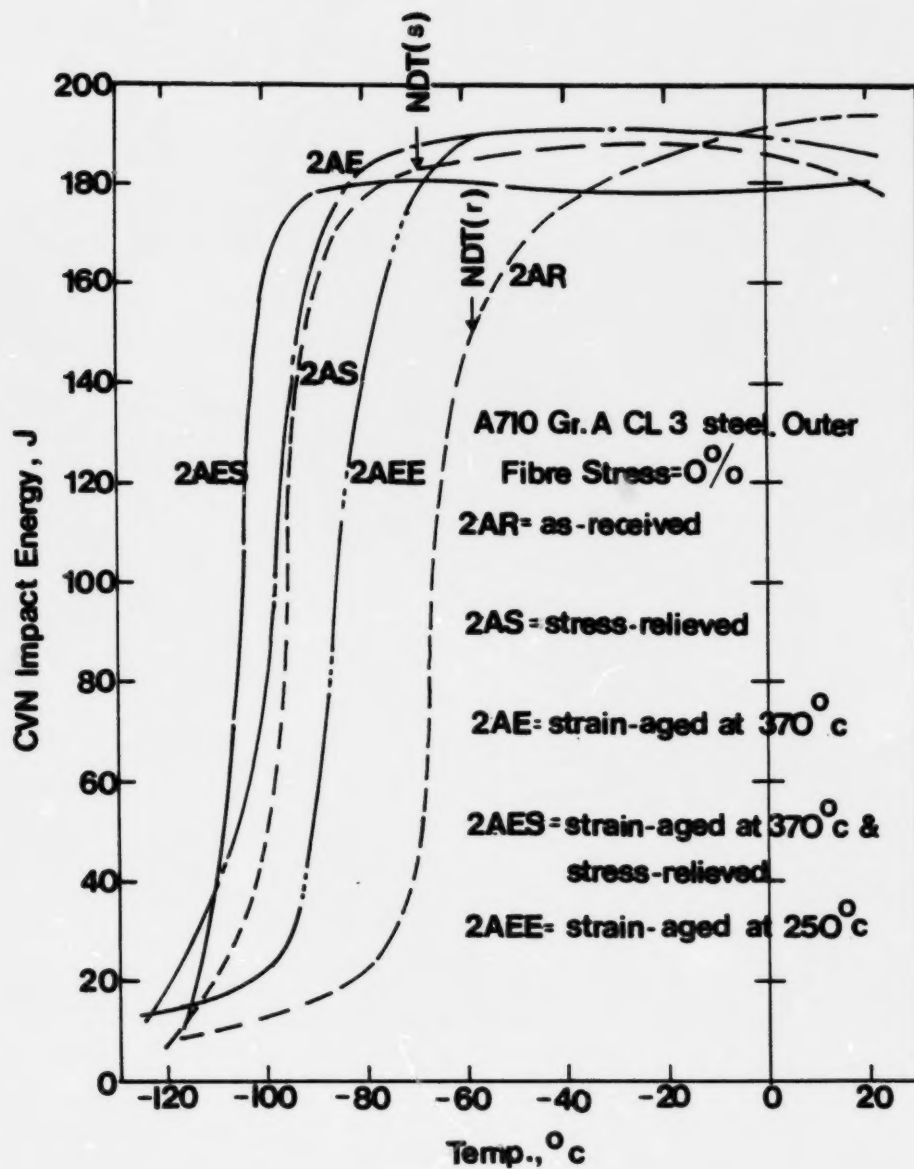


Figure 11: Impact energy transition curves for as-received A710 Gr. A CL 3 steel.

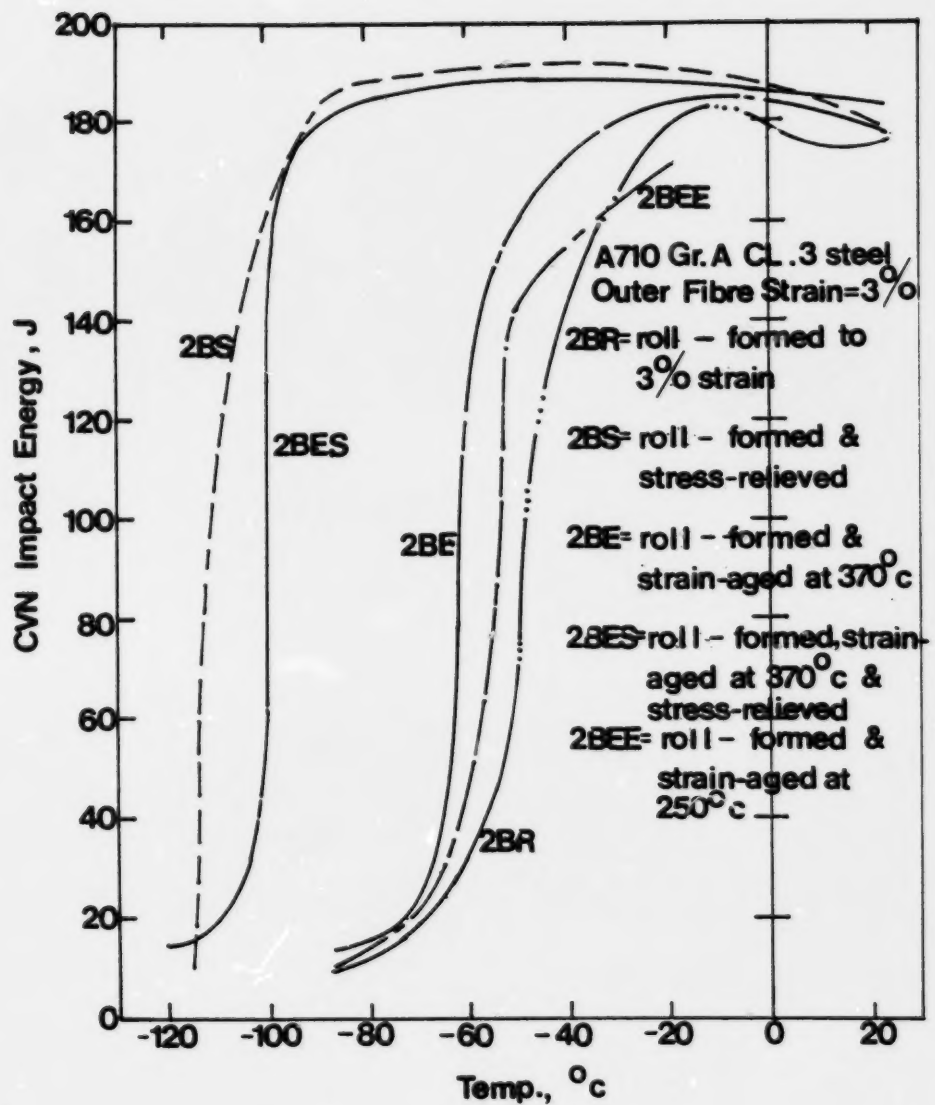


Figure 12: Impact energy transition curves for roll-formed A710 Gr. A Cl 3 steel with 3% outer fibre strain.

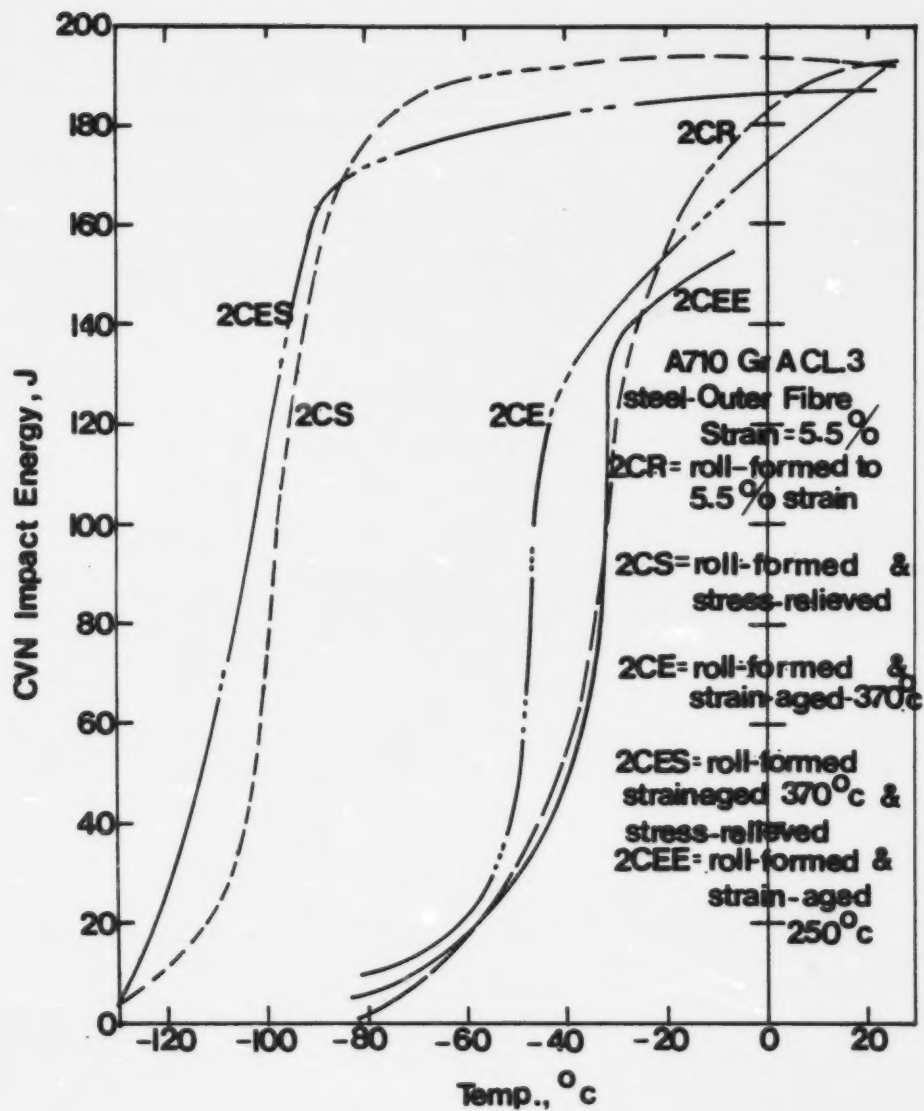
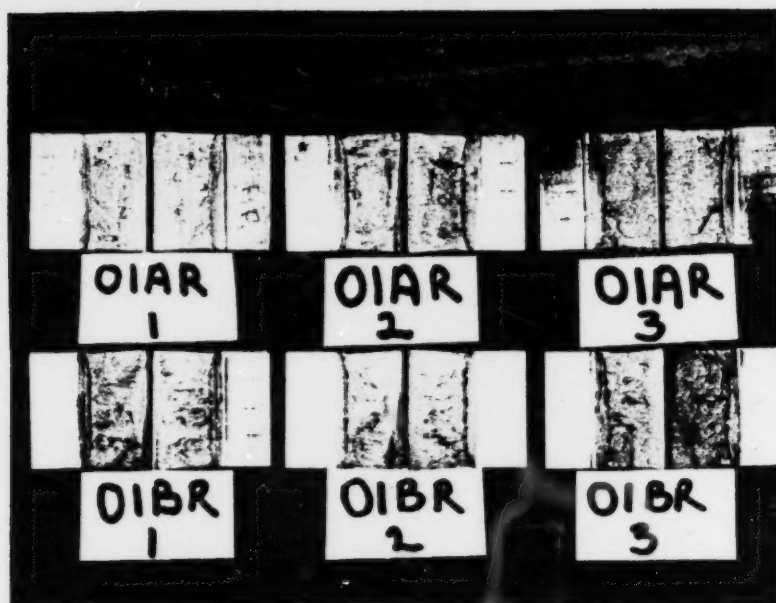
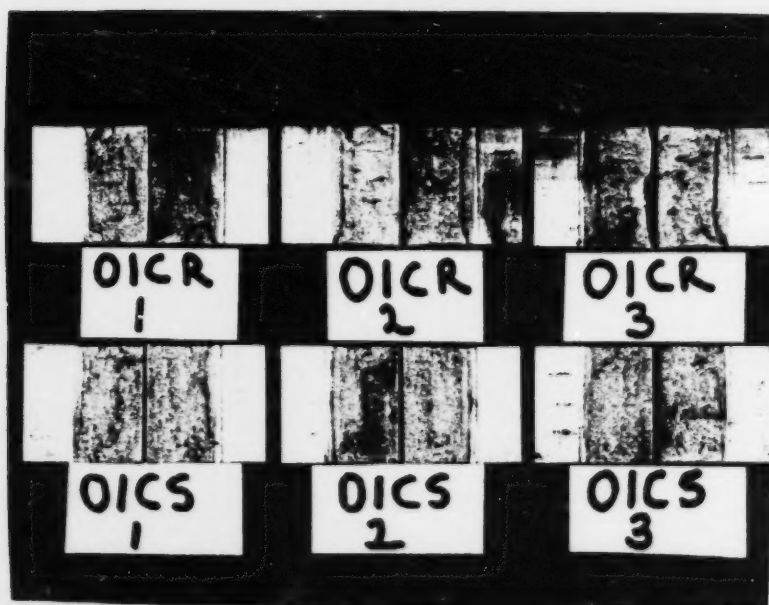


Figure 13: Impact energy transition curves for roll-formed A710 Gr. A Cl 3 steel with 5.5% outer fibre strain.



(a) as-received (AR) and with 3% tensile strain (BR) (Neg. No. 7305)

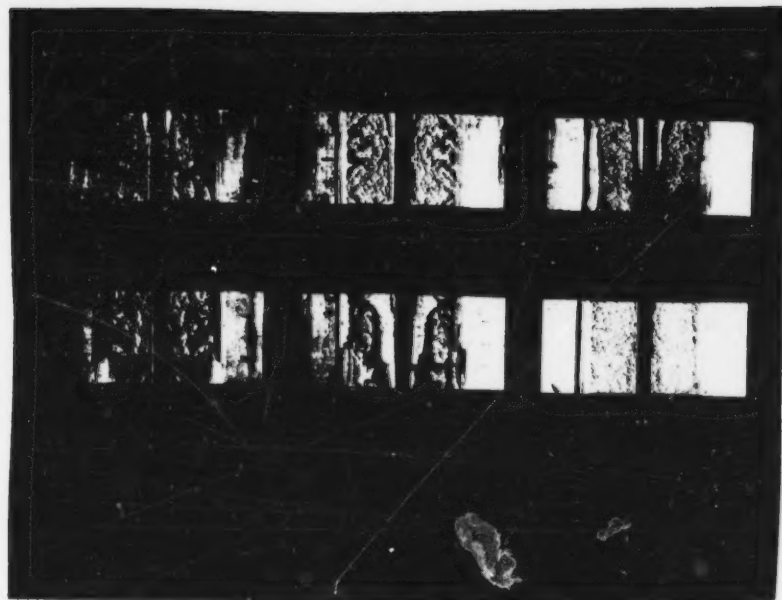


(b) with 6% tensile strain (CR) and with 6% tensile strain + stress-relieved (CS) (Neg. No. 7306)

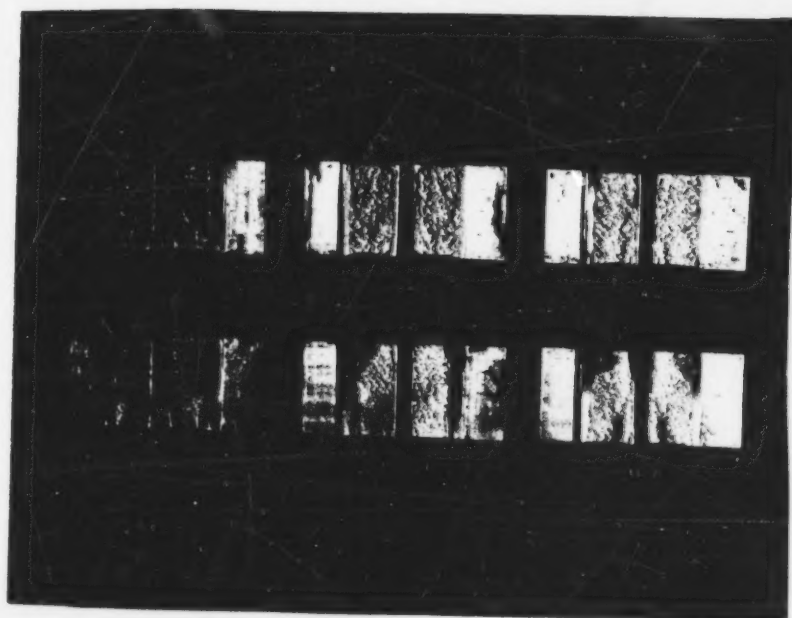


(c) with 6% tensile strain + strain-age at 250°C (CEE) and with 6% tensile strain + strain-aged at 370°C + stress-relieved (CES) (Neg. No. 7307)

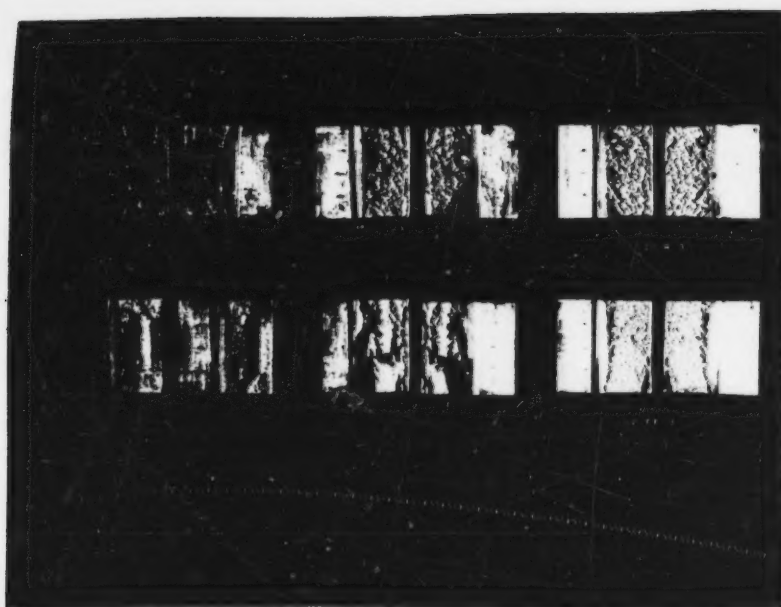
Figure 14 The fractured CTOD specimens of LT60 steel showing fatigue pre-crack, crack initiation region and the over-load failure.



(a) Set 1 Neg. No. 7219



(b) Set 2 Neg. No. 7221

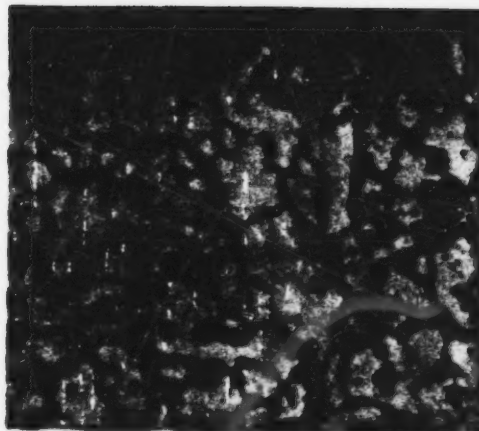


(c) Set 3. Neg. No. 7223.

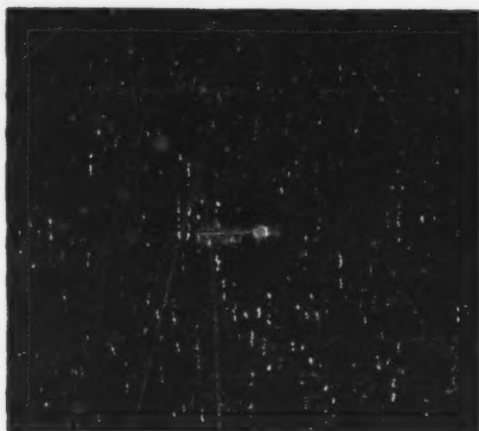
Figure 15 The fractured CTOD specimens of A710 Gr A Cl 3 steel showing fatigue pre-crack, crack initiation region and the overload failure: AR = as-received, BR = with 3% tensile strain, CR = with 5.5% tensile strain, CS = with 5.5% tensile strain + stress-relieved, CES = with 5.5% tensile strain + strain-aged at 370°C + stress-relieved, CEE = with 5.5% strain + strain-aged at 250°C.



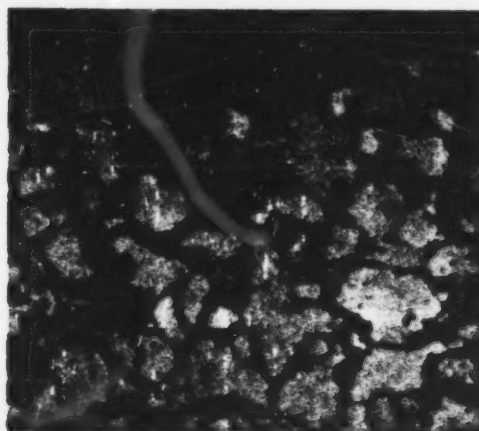
(a) as-received (AR, Neg. No. 7023)



(b) stress-relieved (AS, Neg. No. 7025),



(c) strain-aged at 370°C (AE, Neg. No. 7027)

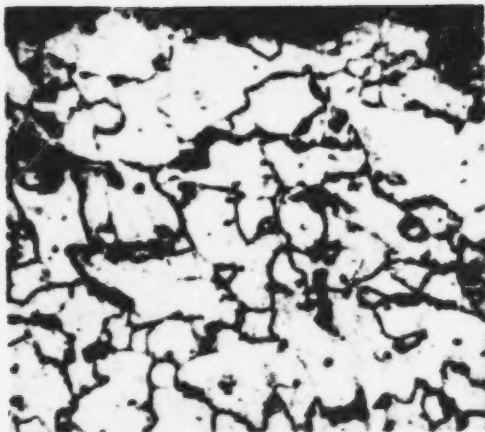


(d) strain-aged at 370°C + stress-relieved (AES, Neg. no. 7021)

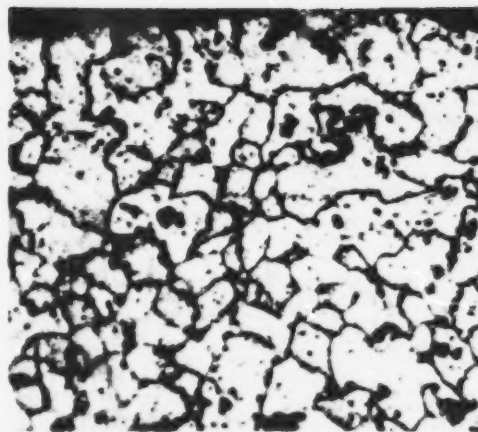


(e) strain-aged at 250°C (AEE, Neg. no. 7030)

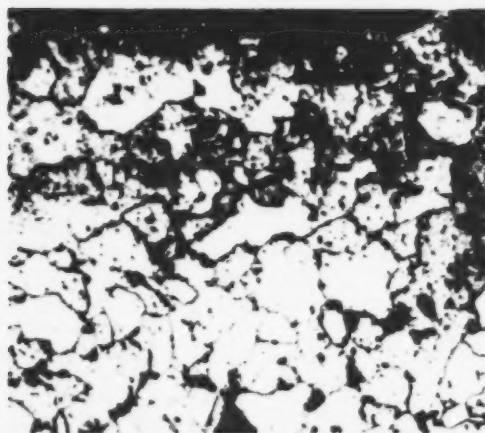
Figure 16. Optical micrographs of regions closer to the outer surface of as-received LT60 steel, nital etch, X800;



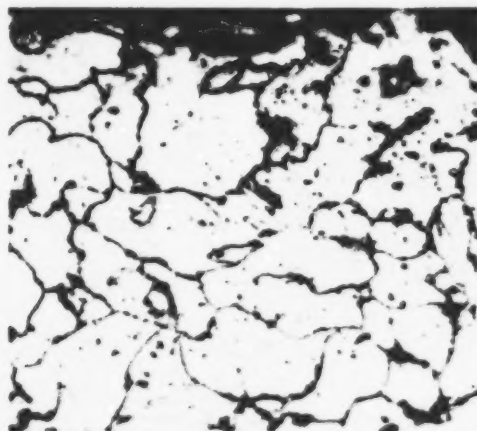
(a) as roll-formed (BR, Neg. No. 7093)



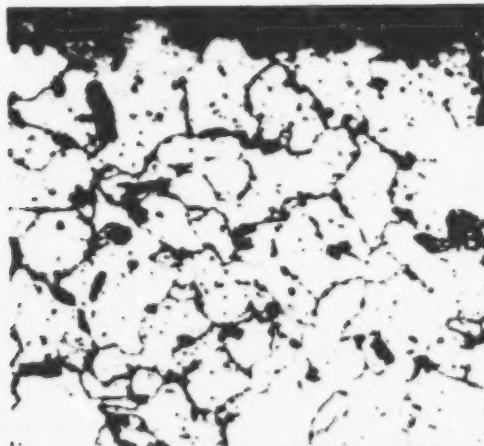
(b) stress-relieved (BS, Neg. no. 7095),



(c) strain-aged at 370°C (BE, Neg. No. 7091)

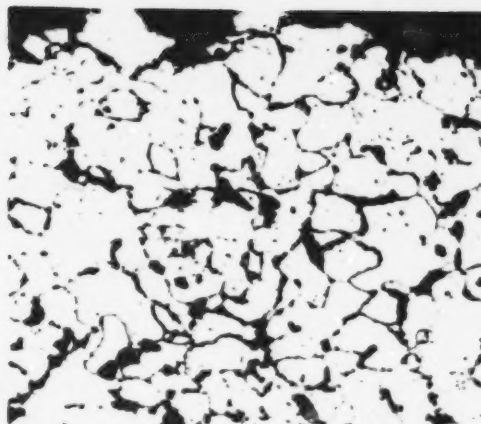


(d) strain-aged at 370°C + stress-relieved (BES, Neg. no. 7099)

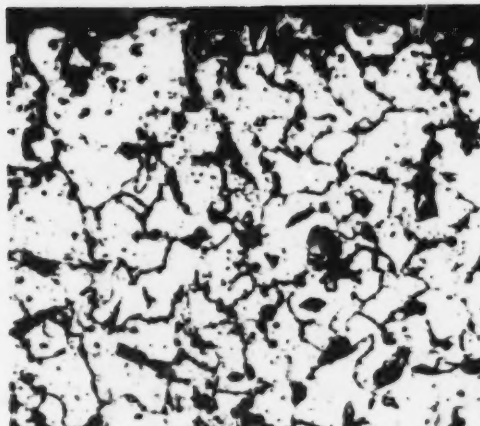


(e) strain-aged at 250°C (BEE, Neg. no. 7097).

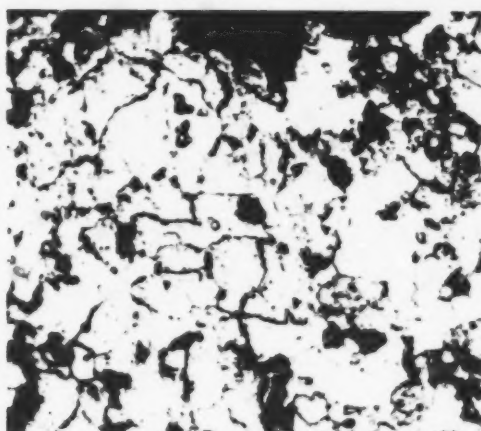
Figure 17. Optical micrographs of regions closer to the outer surface of LT60 steel roll-formed to 3% outer fibre strain, nital etch, X800;



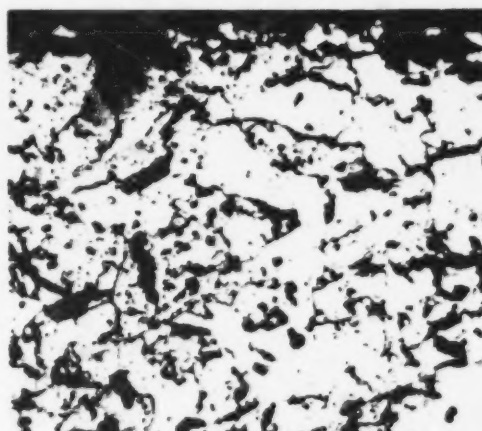
(a) as-roll-formed (CR, Neg. No. 7081)



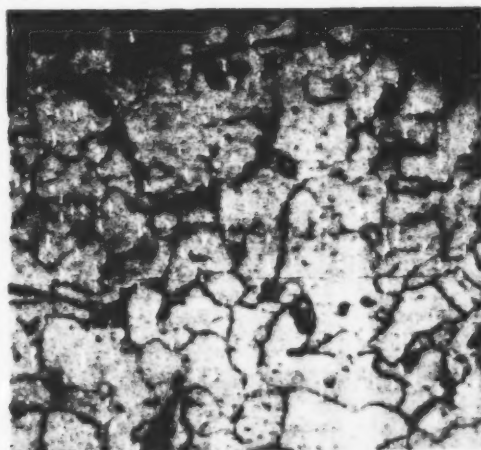
(b) stress-relieved (CS, Neg. No. 7085),



(c) strain-aged at 370°C (CE, Neg. No. 7083)

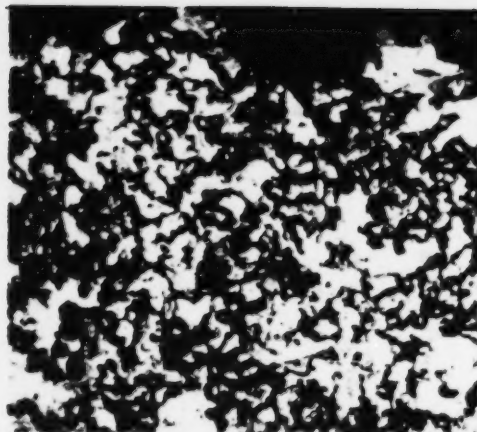


(d) strain-aged at 370°C + stress-relieved (CES, Neg. No. 7087)



(e) strain-aged at 250°C (CEE, Neg. No. 7088)

Figure 18. Optical micrographs of regions closer to the outer surface of LT60 steel roll-formed to 6% outer fibre strain, nital etch, X800;



(a) as-received (AR, Neg. No. 6830), (b) stress-relieved (AS, Neg. No. 6832),

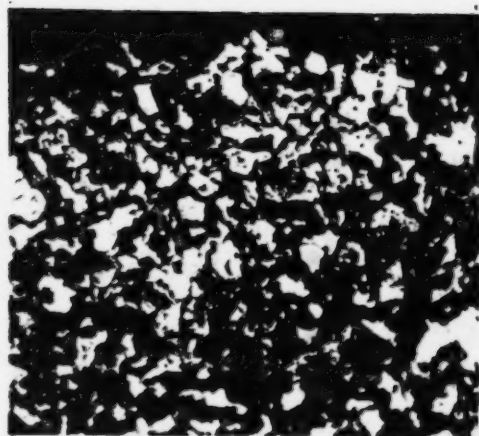


(c) strain-aged at 370°C (AE, Neg. No. 6828) (d) strain-aged at 370°C + stress-relieved (AES, Neg. No. 6826)

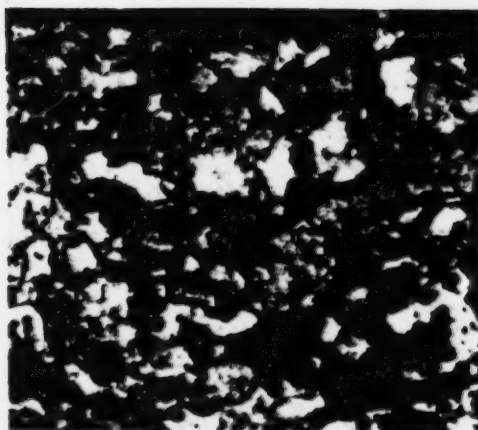


(e) strain-aged at 250°C (AEE, Neg. No. 6854).

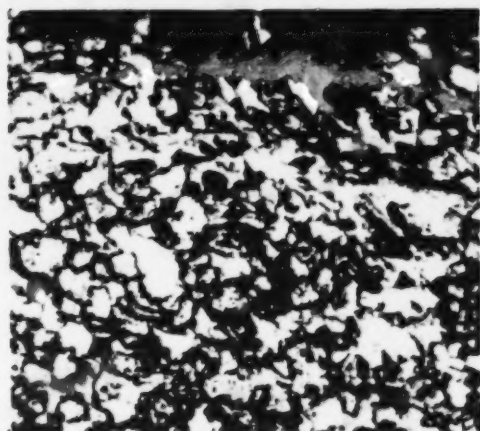
Figure 19 Optical micrographs of regions closer to the outer surface of as-received A710 Gr A Cl 3 steel, nital etch, X800



(a) as-roll-formed (BS, Neg. No. 6838)



(b) stress-relieved (BS, Neg. No. 6840),



(c) strain-aged at 370°C (BE, Neg. No. 6834)

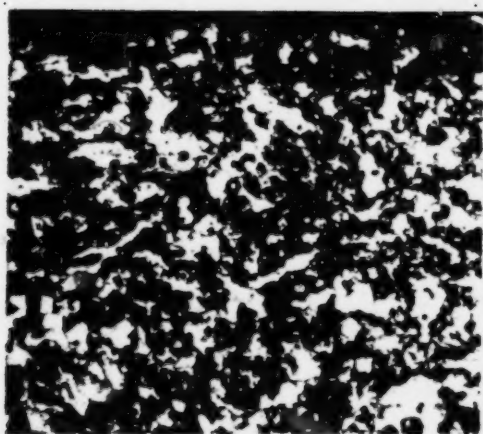


(B) strain-aged at 370°C + stress-relieved (BES, Neg. No. 6836)

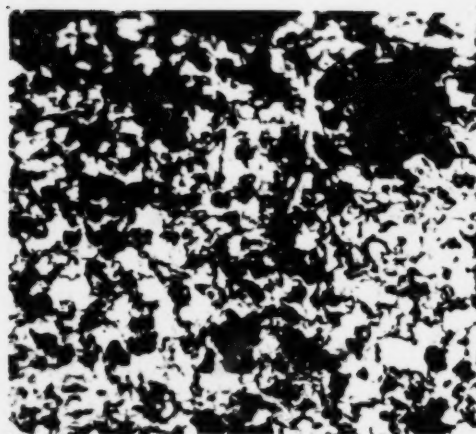


(e) strain-aged at 250°C (BEE, Neg. No. 6856).

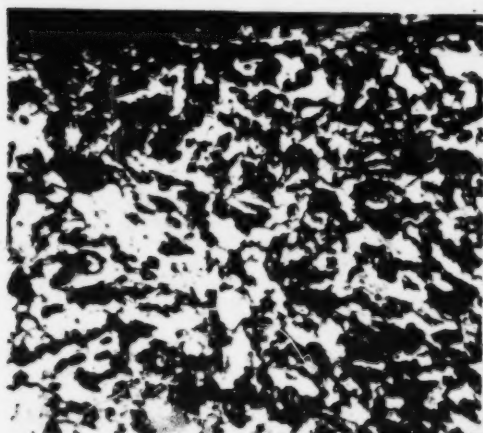
Figure 20. Optical micrographs of regions closer to the outer surface of A710 Gr A Cl 3 roll-formed to 3% outer fibre strain, nital etch, X800;



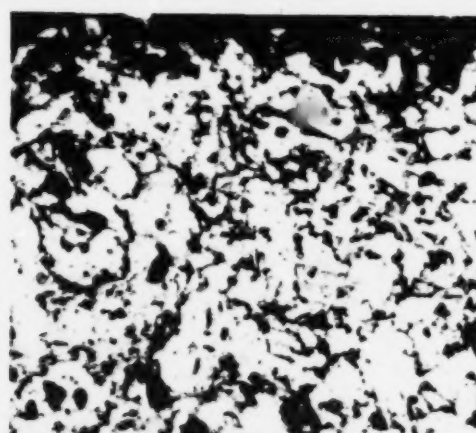
(a) as-roll-formed (CR, Neg. No. 6846)



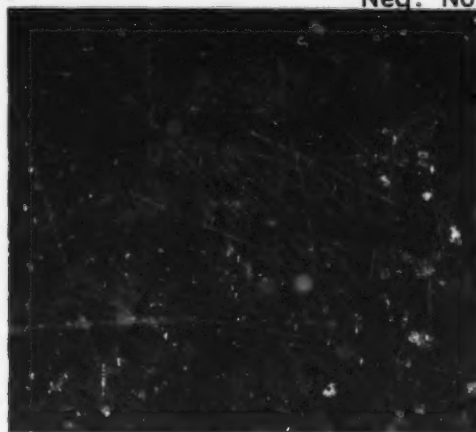
(b) stress-relieved (CS, Neg. No. 6848)



(c) strain-aged at 370°C (CE, Neg. No. 6842)

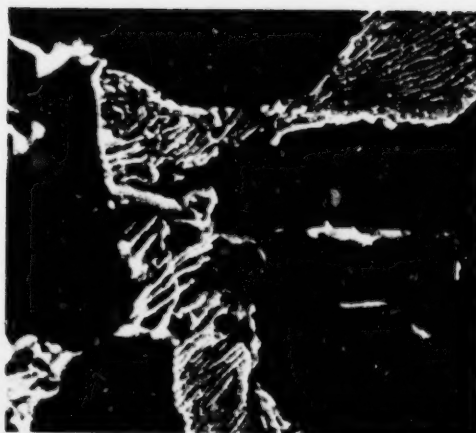


(d) strain-aged at 370°C + stress-relieved (CES, Neg. No. 6844)

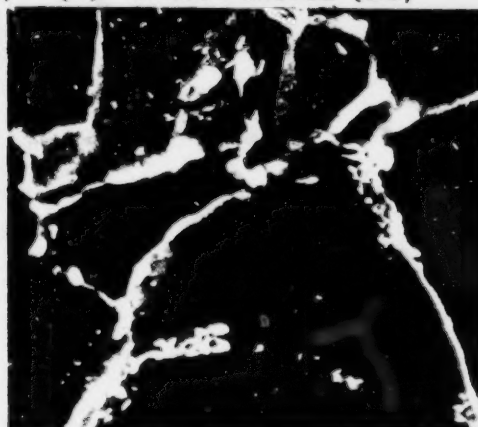
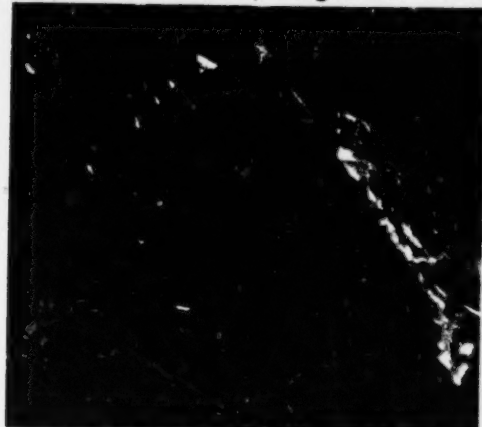


(e) strain-aged at 250°C (CEE, Neg. No. 6858)

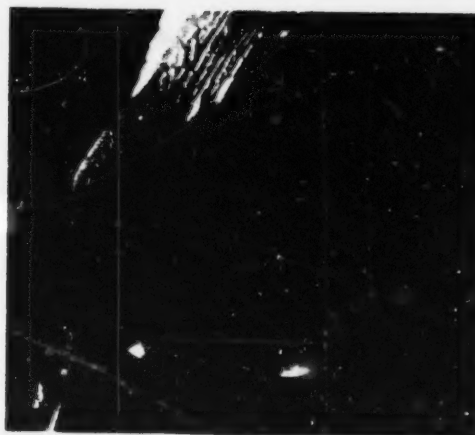
Figure 21 Optical micrographs of regions closer to the outer surface of A710 Gr A Cl steel roll-formed to 6% outer fibre strain, nital etch, X800;



(a) as-formed (BR, Neg. No. 7311), (b) stress-relieved (BS,

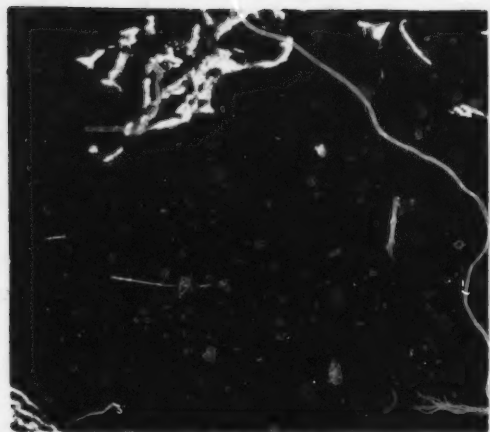


(c) strain-aged at 370°C (BE, Neg. No. 7315) (d) strain-aged at 370°C + stress-relieved (BES, Neg. No. 7319)

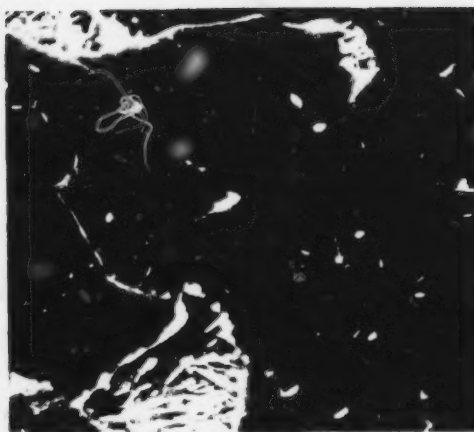


(e) strain-aged at 250°C (BEE, Neg. No. 7323)

Figure 22 Scanning electron micrographs of regions closer to the outer surface of LT60 steel roll-formed to 3% outer fibre strain, nital etch, X5400;



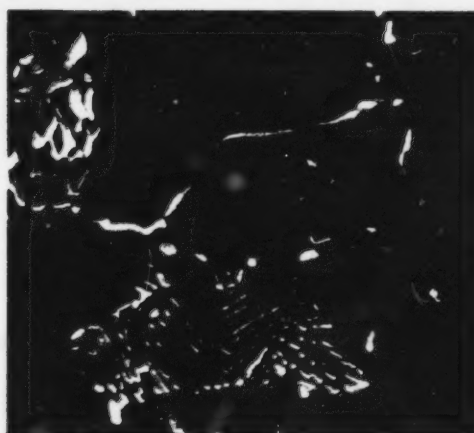
(a) as-formed (CR, Neg. No. 7324),



(b) stress-relieved (CS, Neg. No. 7326),



(c) strain-aged at 370°C (CE, Neg. No. 7327)

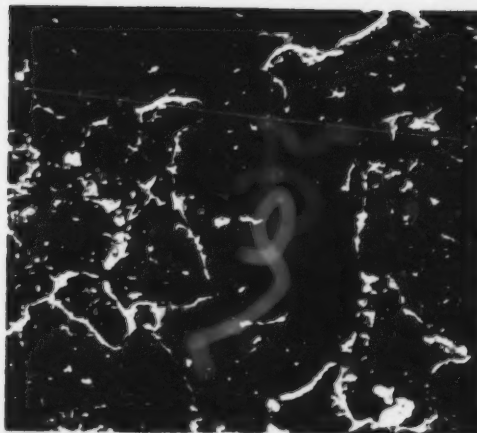
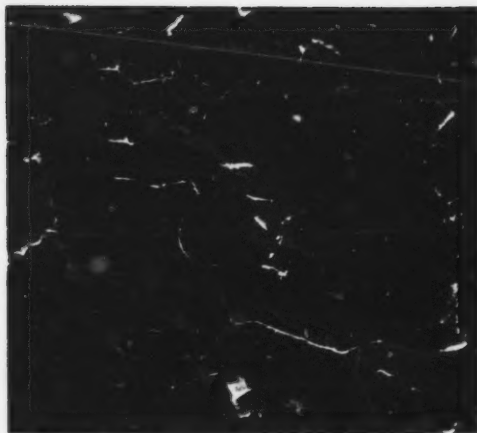


(d) strain-aged at 370°C + stress-relieved (CES, Neg. No. 7330)

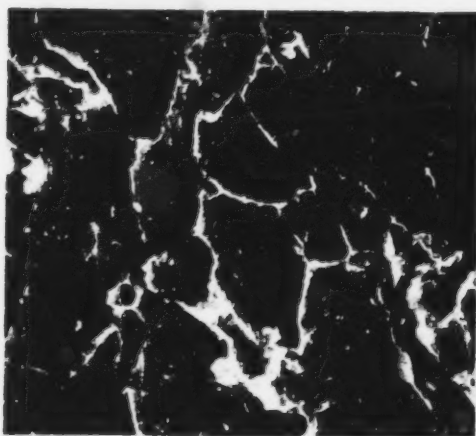


(e) strain-aged at 250°C (CEE, Neg. No. 7331)

Figure 23 Scanning electron micrographs of regions closer to the outer surface of LT60 steel, roll-formed to 6% outer fibre strain, nital etch, X5400;



(a) as-received (AR, Neg. No. 7334), (b) stress-relieved (AS, Neg. No. 7336),



(c) strain-aged at 370°C (AE, Neg. No. 7338)

(d) strain-aged at 370°C + stress-relieved (AES, Neg. No. 7339)

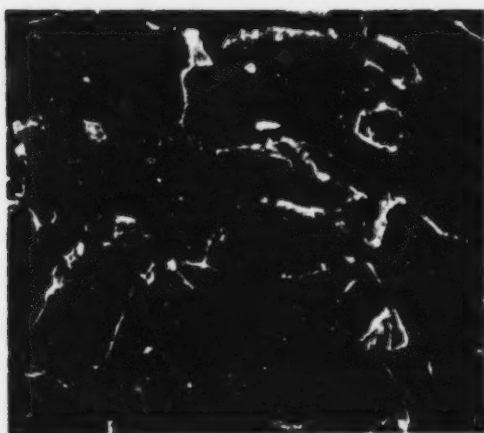
Figure 24 Scanning electron micrographs of as-received A710 Gr A CI 3 steel, nital etch, X5400;



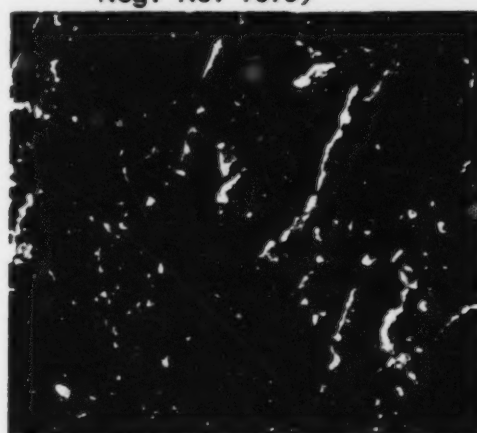
(a) as-formed (CR, Neg. No. 7371)



(b) stress-relieved (CS, Neg. No. 7373)



(c) strain-aged at 370°C (CE, Neg. No. 7375)

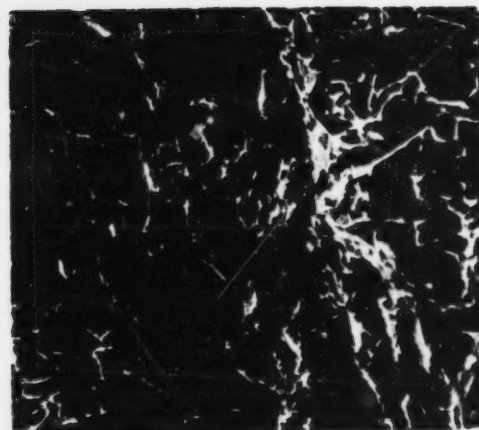


(d) strain-aged at 370°C + stress-relieved (CES, Neg. No. 7378)

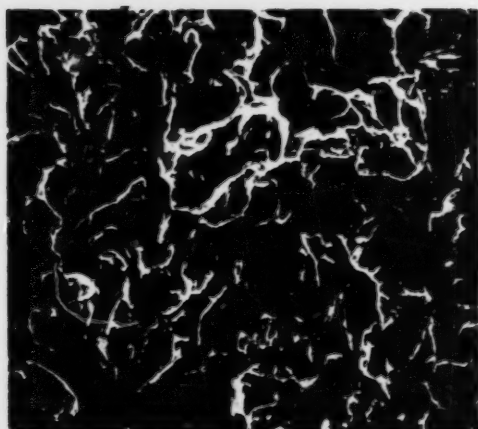
Figure 25 Scanning electron micrographs A710 Gr A Cl steel roll-formed to 5.5% outer fibre strain (regions closer to the outer surface), nitral etch, X5400;



(a) as-received tested at -100°C
(Neg. No. 7559)



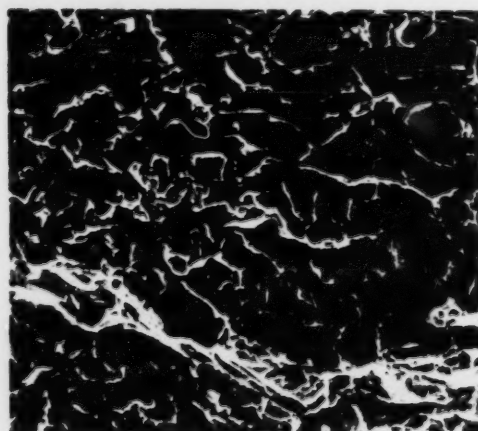
(b) as-received + strain-
aged at 370°C + stress
relieved, tested at
 -120°C (Neg. No. 7555)



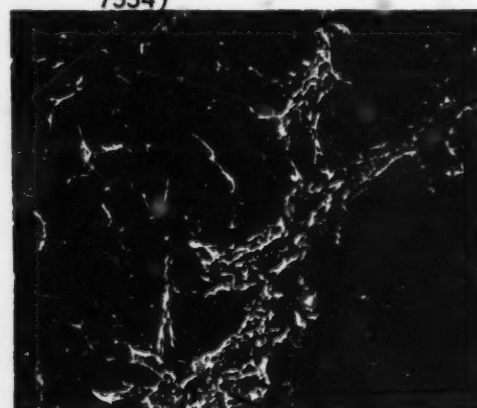
(c) 3% outer fibre strain tested
at -110°C (Neg. No. 7256)



(d) outer fibre strain +
strain aged at 370°C +
stress-relieved, tested
at -90°C (Neg. No.
7554)



(e) 3% outer fibre strain +
strain-aged at 250°C , tested
at -110°C (neg. No. 7258)



(f) 6% outer fibre strain,
tested at -80°C (Neg.
No. 7261)

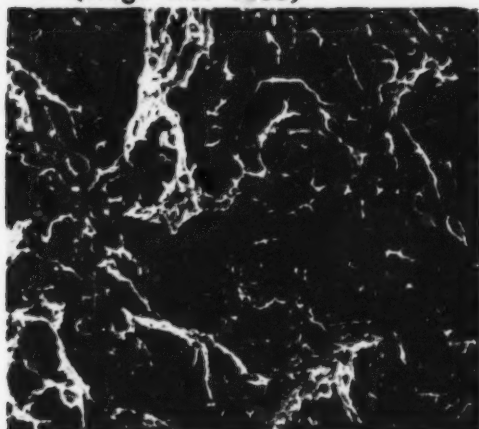
Figure 26 Fractographs of the brittle region of the CVN specimens
for LT60 steel; X480.



(a) as-received tested at -110°C
(Neg. No. 7558)



(b) as-received + stress-relieved, tested at -120°C (Neg. No. 7252)



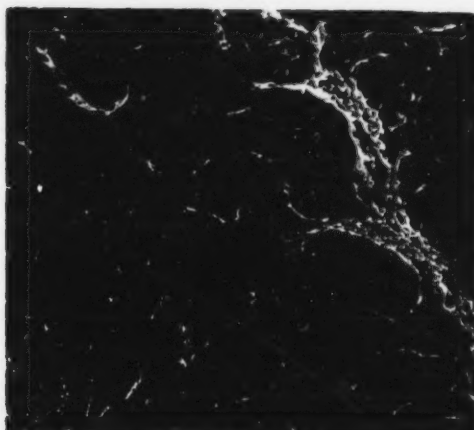
(c) as-received + strain-aged at 370°C tested at -120°C (Neg. No. 7250)



(d) 3% outer fibre strain tested at -50°C (Neg. No. 7245)

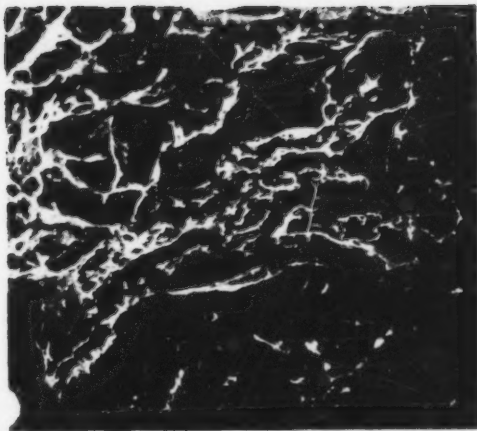


(e) 6% outer fibre strain tested at -70°C (Neg. No. 7561)

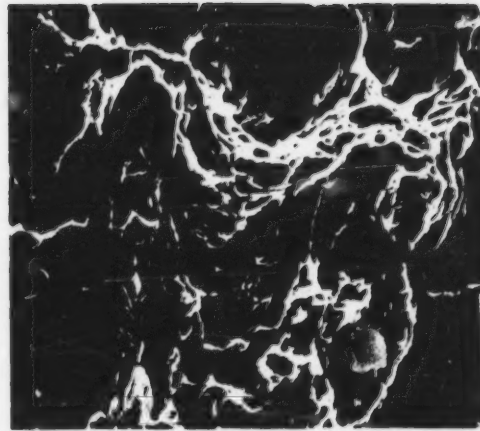


(f) 6% outer fibre strain + stress-relieved tested at -100°C (Neg. No. 7560).

Figure 27 Fractographs of the brittle region of the CVN specimens for A710 Gr A Cl 3 steel, X480;



(a) as-received, CTOD = 1.285mm, X1000 (AR-3, Neg. No. 7359).



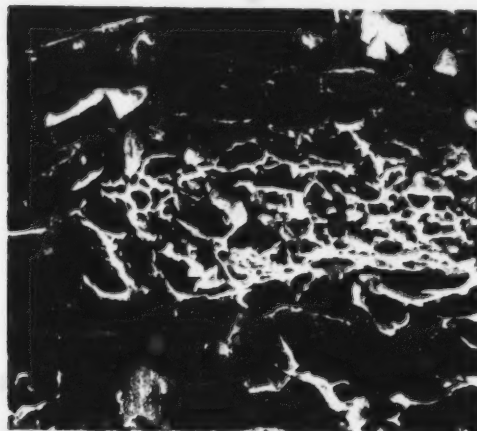
(b) 3% outer fibre strain, CTOD = 1.40mm, X1000 (BR-2 Neg. No. 7363).



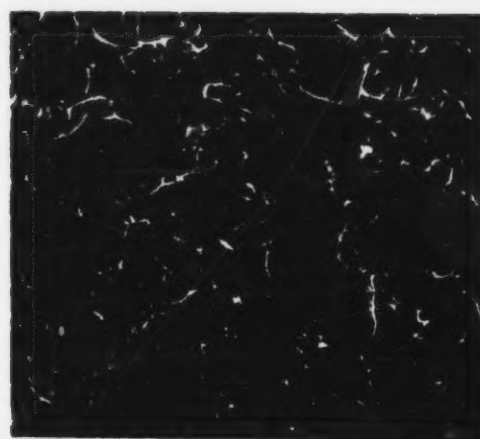
(c) 6% outer fibre strain + strain-aged at 250°C, CTOD = 0.277mm, X1000 (CEE-2, Neg. No. 7557)



(d) same as (c) X2600 (CEE-2, Neg. No. 7556)



(e) same condition as (c), CTOD = 0.18mm, X1000, (CEE-3, Neg. No. 7366).



(f) 6% outer fibre strain + strain-aged at 370°C + stress-relieved, CTOD = 0.14mm, X480 (CES-3, Neg. No. 7364)

Figure 28 Fractographs of fracture initiation region of CTOD specimens for LT60 steel;

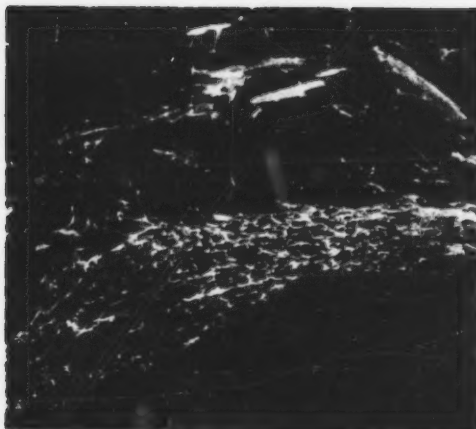


Figure 29 Fractograph of fracture initiation region of CTOD specimen for A710 Gr A Cl 3 steel roll-formed to 5.5% outer fibre strain and stress-relieved, CTOD = 0.178mm, X1000 (CS-1, Neg. no. 7244)

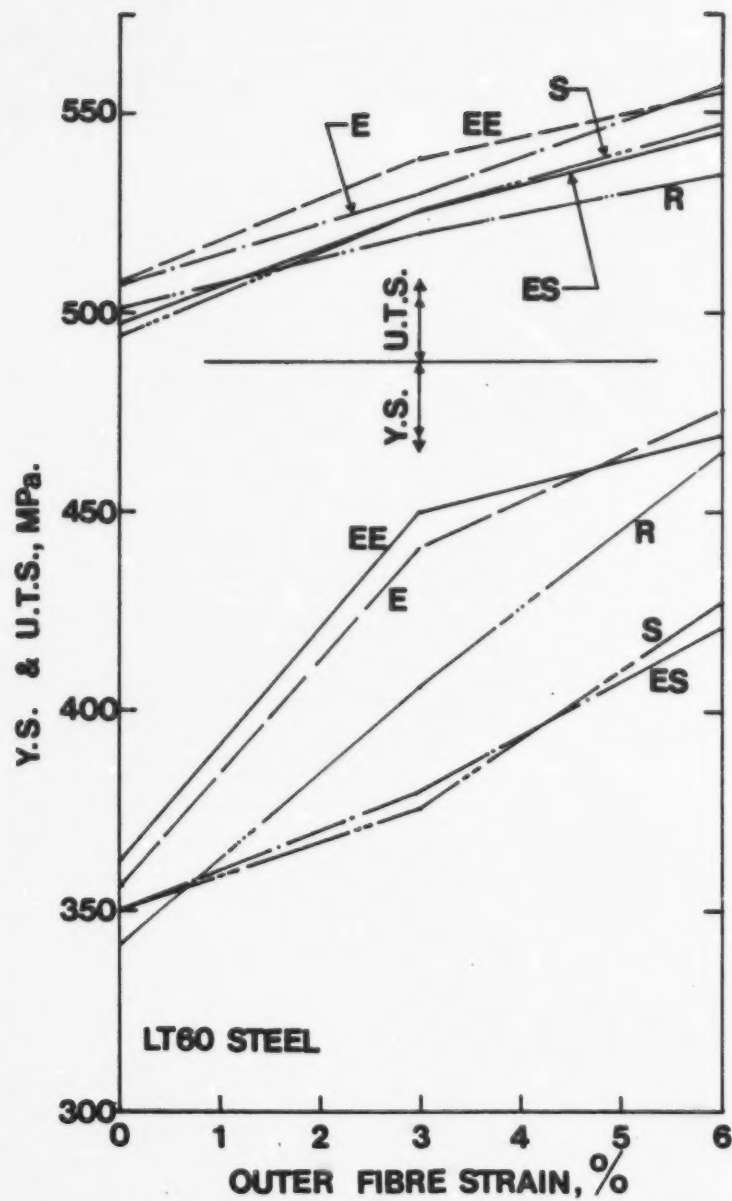


Figure 30: YS and UTS values vs. outer fibre strain for LT60 steel.

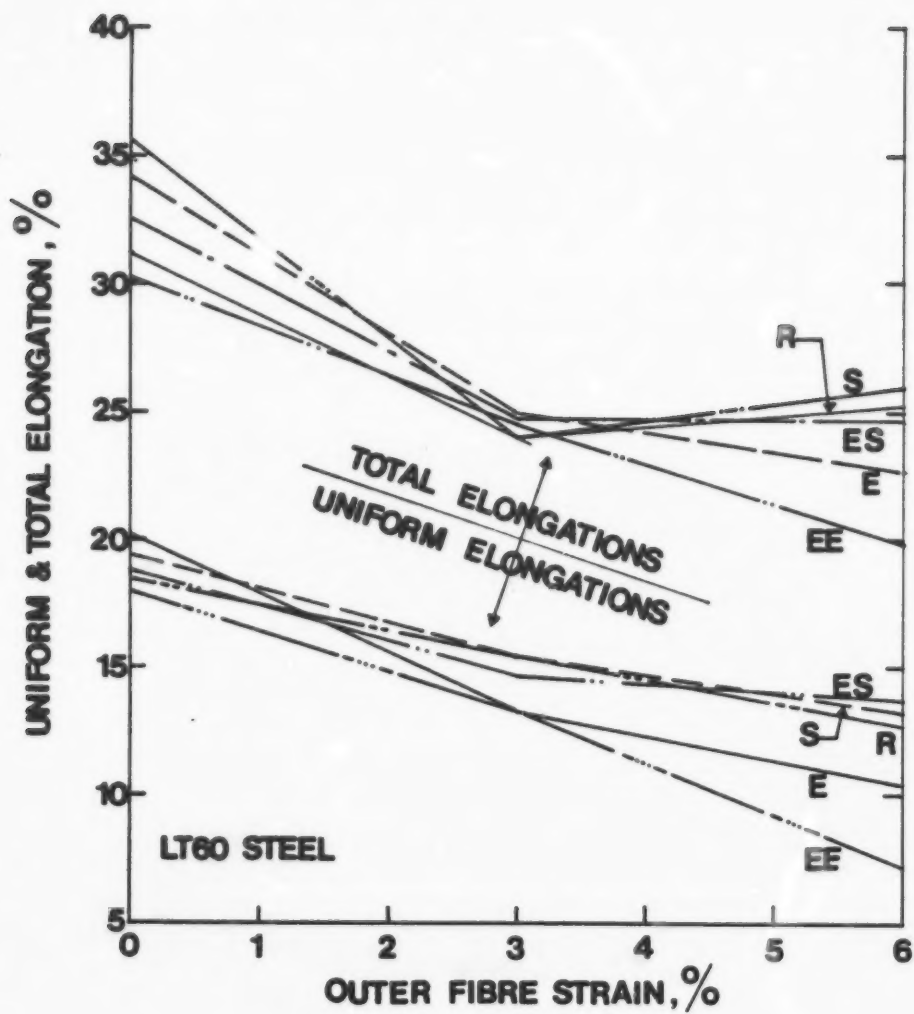


Figure 31: Uniform and total elongation values vs. outer fibre strain for LT60 steel.

A710 GR.A CL 3, STEEL, 64mm thick

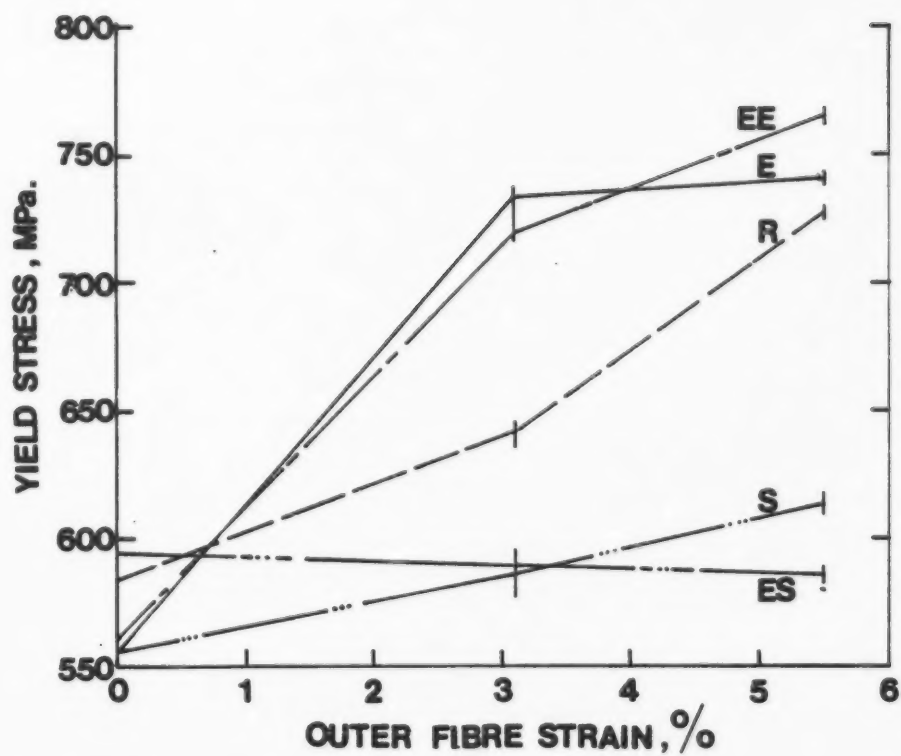


Figure 32: YS vs. outer fibre strain for A710 Gr. A Cl 3 steel.

A710 GR. A CL. 3 STEEL, 64mm thick

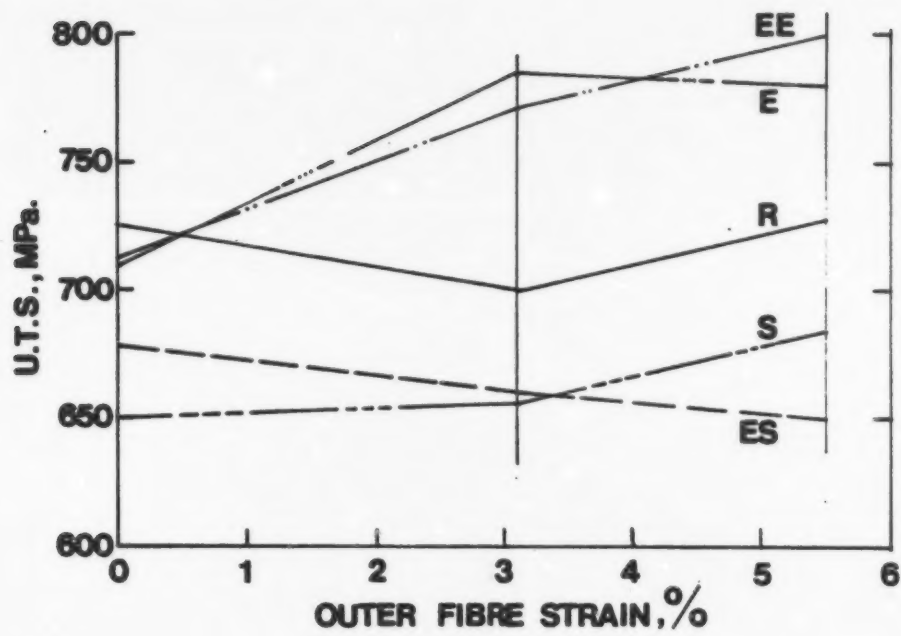


Figure 33: UTS vs. outer fibre strain for A710 Gr. A Cl 3 steel.

A710 GR.A CL.3 STEEL, 64mm thick

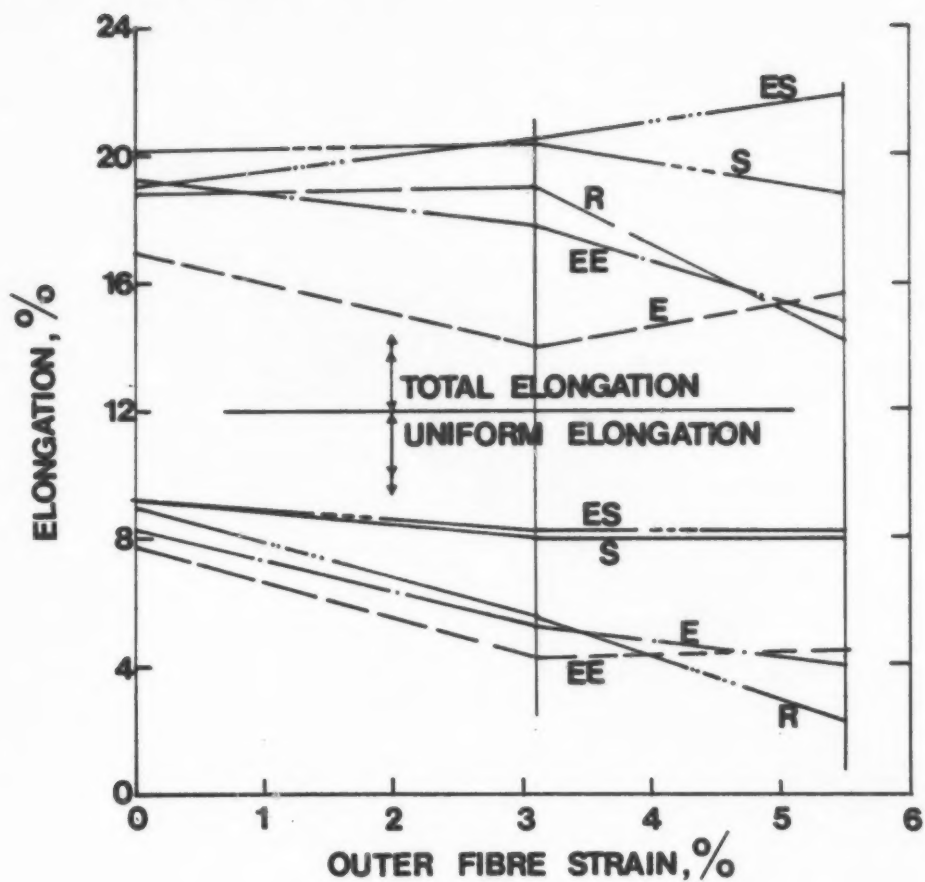


Figure 34: Total and uniform elongation values vs. outer fibre strain for A710 Gr. A Cl 3 steel.

LT60 STEEL

TEST TEMP. = -60°C

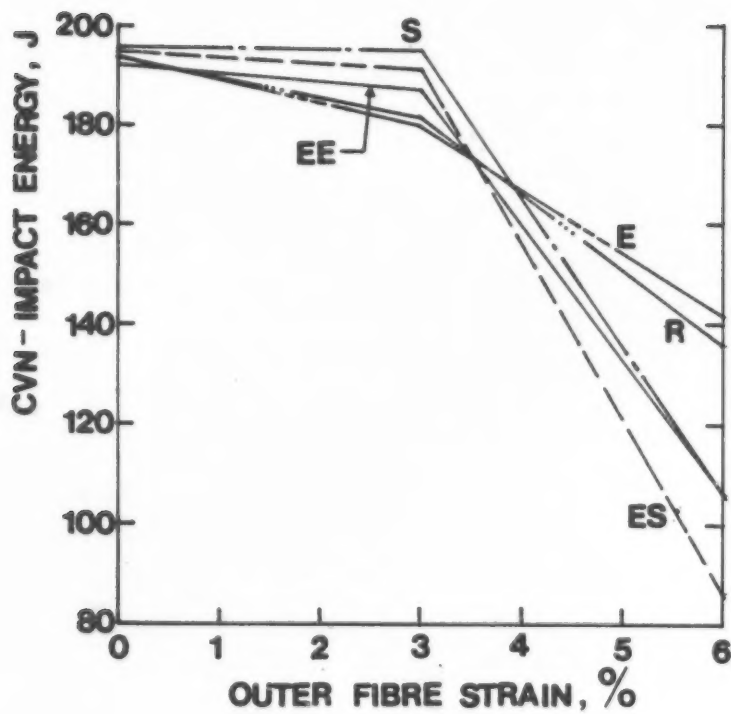


Figure 35: CVN impact energy at -60°C vs. outer fibre strain for LT60 steel.

LT60 STEEL

TEST TEMP = -30°C

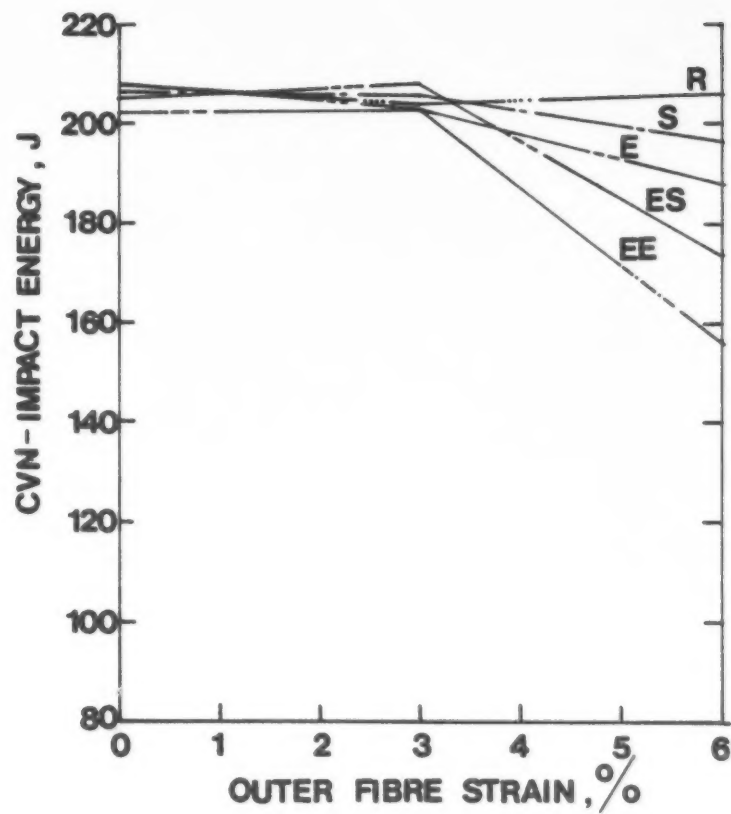


Figure 36: CVN impact energy at -30°C vs. outer fibre strain for LT60 steel.

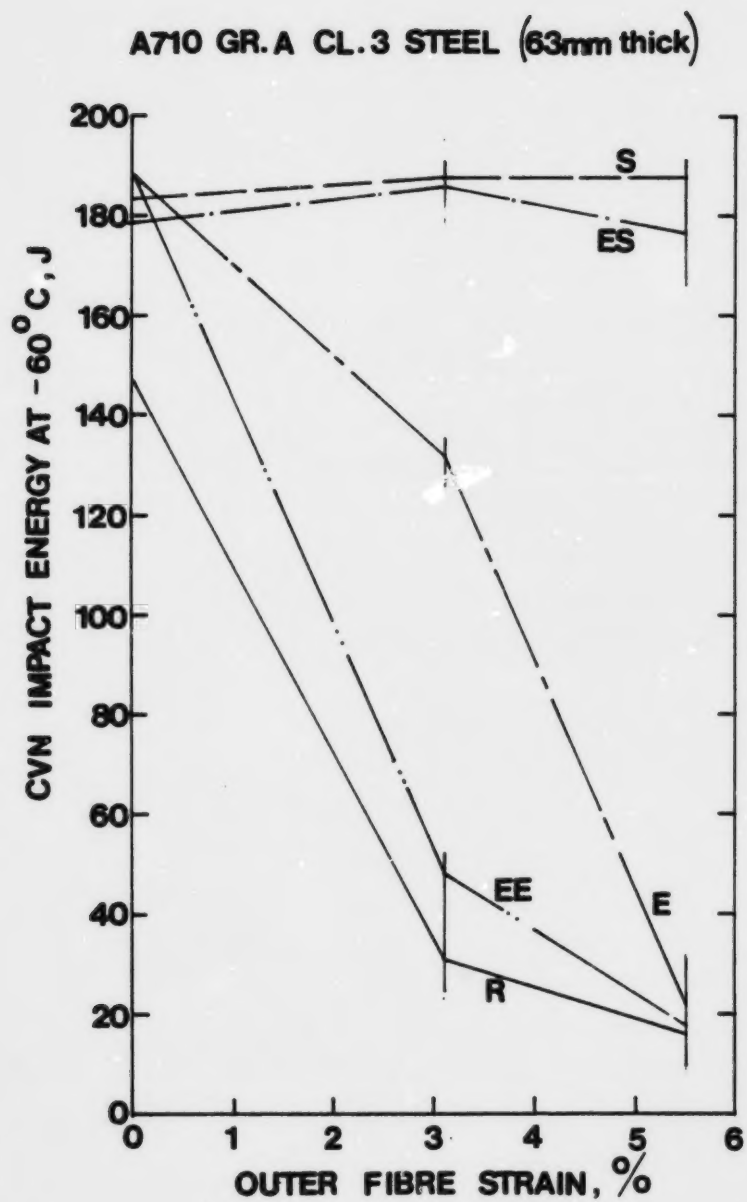


Figure 37: CVN impact energy at -60°C vs. outer fibre strain for A710 Gr. A Cl 3 steel.

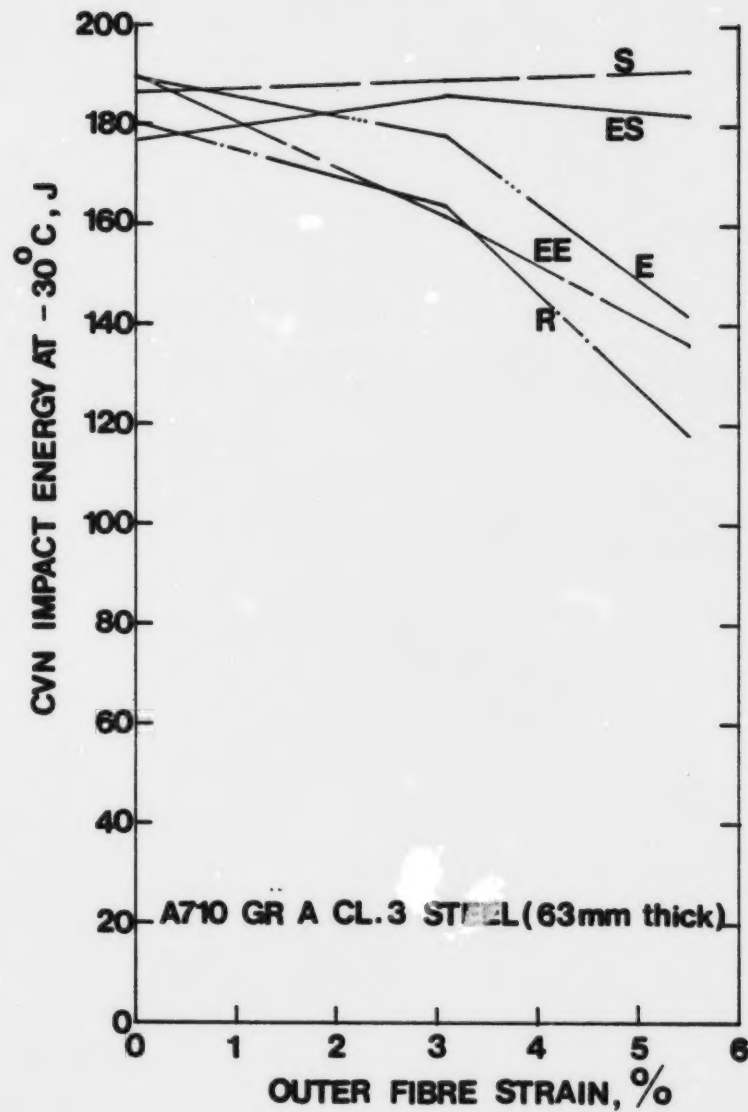


Figure 38: CVN impact energy at -30°C vs. outer fibre strain for A710 Gr. A Cl 3 steel.

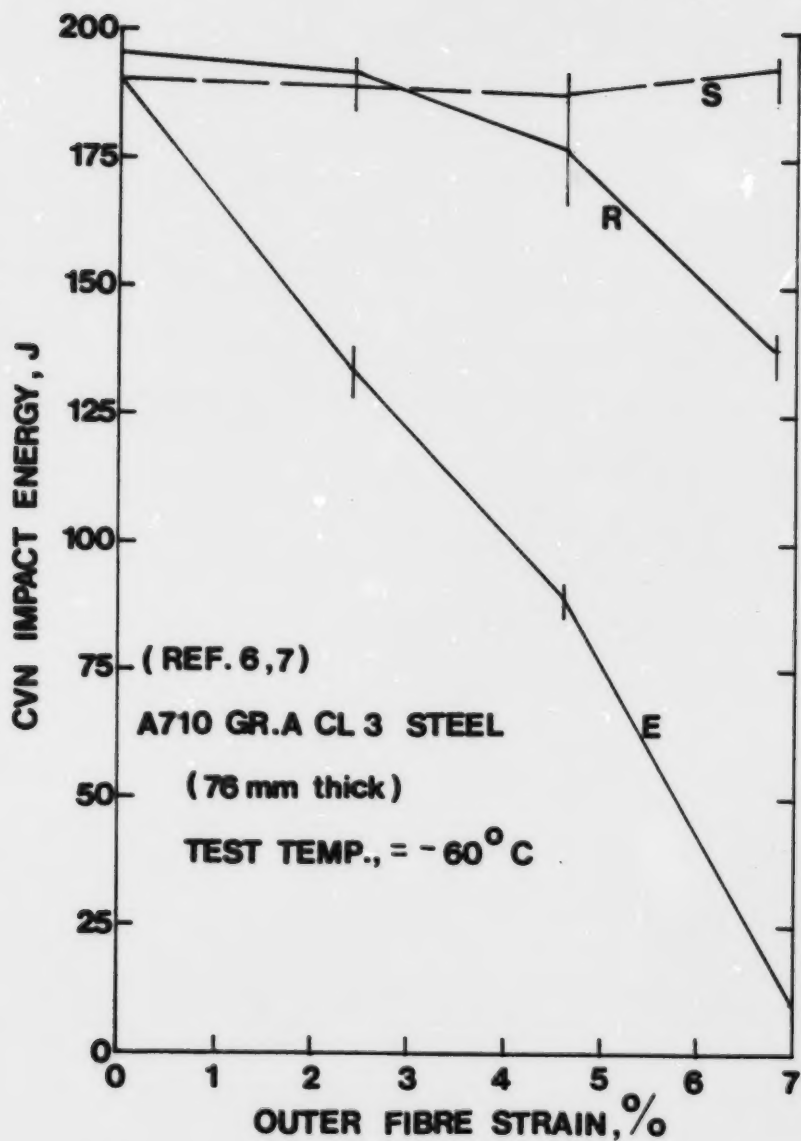


Figure 39: CVN impact energy at -60°C vs. outer fibre strain for A710 Gr. A Cl 3 steel (Ref. 6,7).

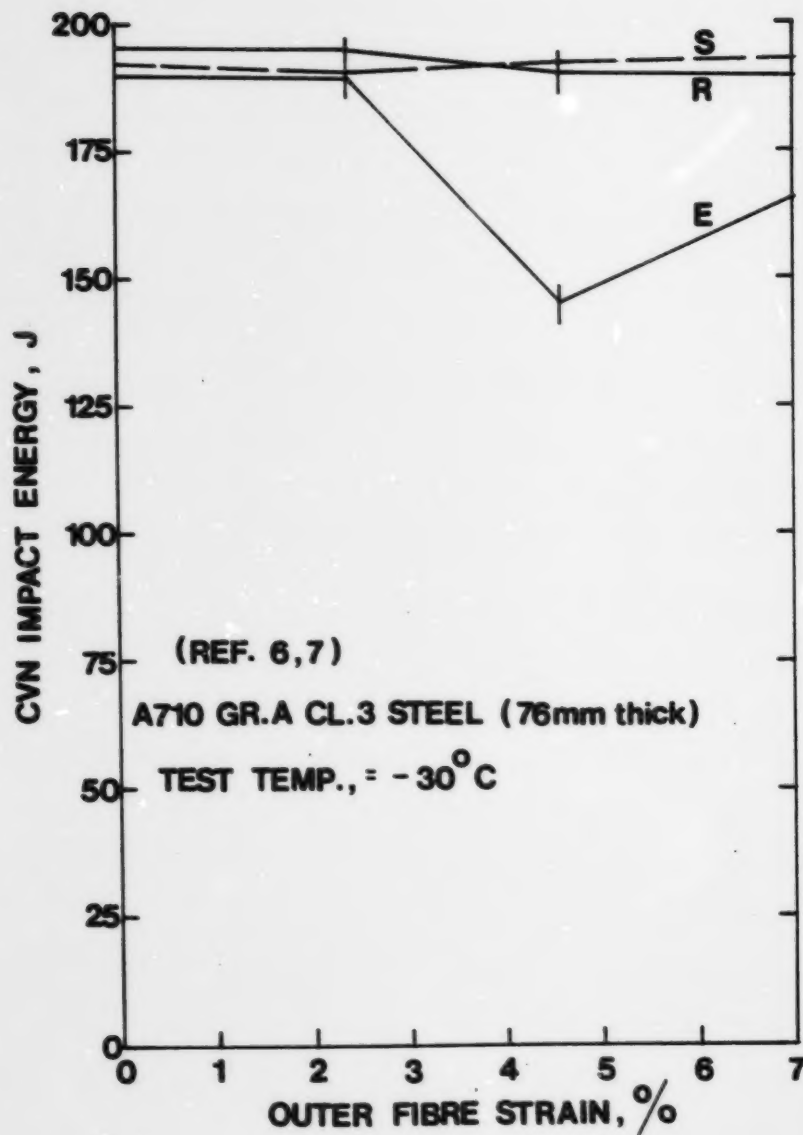


Figure 40: CVN impact energy at -30°C vs. outer fibre strain for A710 Gr. A Cl 3 steel (Ref. 6,7).

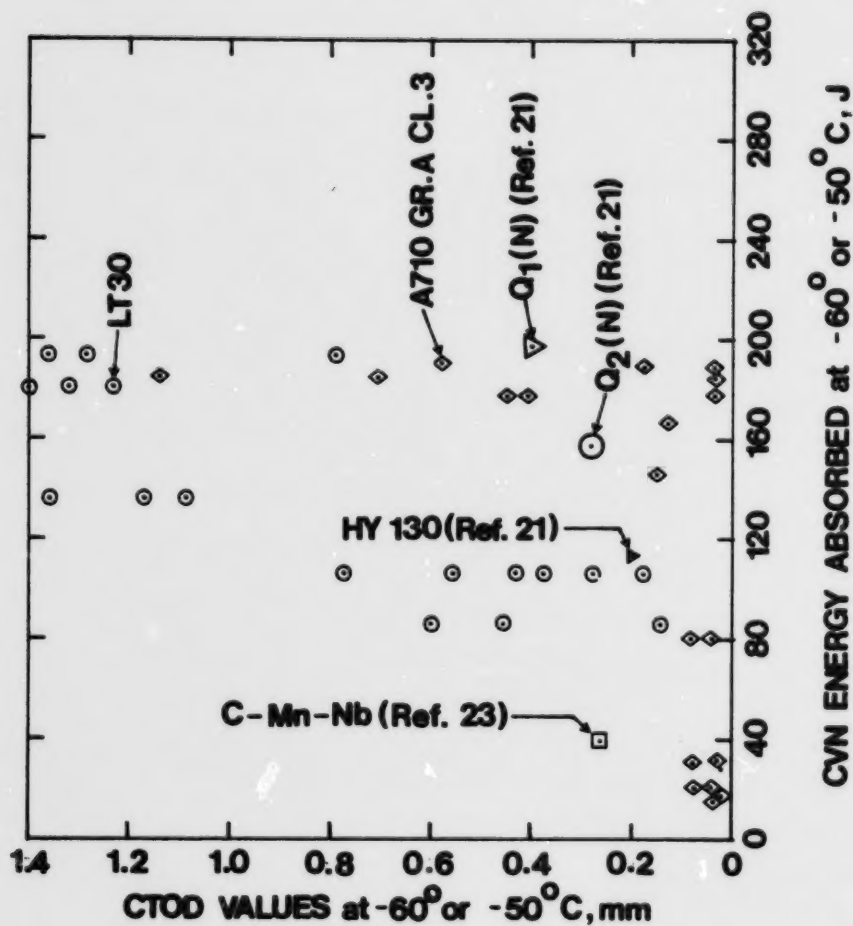


Figure 41: CTOD values vs. CVN values plots at test temperatures of -60°C or -50°C for LT60 and A710 Gr. A Cl 3 steel.

TABLE 1: Chemical Compositions of the Candidate Steels

Elements	Chemical Composition, Weight %			
	A710 Gr A Cl 3 Steel		LT 60 Steel	
	Mill Test	Technitrol	Mill Test	Technitrol
C	0.04	0.06	0.12	0.12
Mn	0.70	0.67	1.39	1.29
Si	0.35	0.31	0.28	0.26
P	0.010	0.010	0.017	0.010
S	0.005	0.006	0.011	0.006
Cr	0.84	0.91	0.17	0.15
Ni	0.94	1.04	0.15	0.10
Mo	0.19	0.15	--	0.03
Cu	1.19	1.16	0.15	0.15
Nb (Cb)	0.044	0.04	0.041	0.039
V	--	<0.01	0.053	0.05
O	--	0.0024	--	0.0035
		(24 ppm)		(35 ppm)
N	--	0.012	--	0.0063
		(120 ppm)		(63 ppm)
Al	--	0.027	0.027	0.03

TABLE 2: Specimen Conditions and Test Temperatures
for the CTOD Tests.

Identification	Conditions	Number of specimens tested at test temperatures					
		-60°C		-50°C		-30°C	
		LY60 Steel	A710 Gr A Cl 3 Steel	LY60 Steel	A710 Gr A Cl 3 Steel	LY60 Steel	A710 Gr A Cl 3 Steel
XAR	As-received	3	2	0	1	0	0
XAS	As-received + stress-relieved	0	1	0	2	0	0
XBR	Roll-formed to 3% strain	3	1	0	2	0	3
XCR	Roll-formed to 5.5 or 5% strain	3	1	0	2	0	0
XCS	Roll-formed to 5.5 or 6% strain + stress-relieved	3	2	0	1	0	0
XCES	Roll-formed to 5.5 or 6% strain + strain age at 370°C + stress- relieve	3	3	0	0	0	0
XCEE	Roll-formed to 5.5 or 6% strain + strain age at 250°C	3	1	0	2	0	0

TABLE 3: Mechanical Test Data for LT60 Steel (1)

THICKNESS: 63.5mm

SOURCE: ALGOMA STEEL CORP.

OUTER FIBRE STRAIN: 0% (A)

GRAIN SIZE: AVERAGE G.S.
= ASTM 8

MICROSTRUCTURE: FERRITE + PEARLITE

TENSILE TEST DATA (LONGITUDINAL)															
CONDITION	R			S			E			ES			EE		
YS(0.2%) MPa	342			350			363			350			357		
UTS MPa	501			496			508			497			507		
TOT. ELN. %	31.2			35.6			34.2			32.5			30.2		
UNI. ELN. %	18.5			19.4			20.1			18.8			18.0		
RA %	77.9			78.1			78.8			78.1			78.4		
IMPACT TEST DATA (LONGITUDINAL)															
Temp. °C	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %
31.2	188	2.34	NB	188	2.50	NB	141	2.38	NB	176	2.38	NB	173	2.34	NB
31.2															
5.6	207	2.34	NB	204	2.24	NB	108	2.24	NB	204	2.21	NB	208	2.29	NB
5.6															
-14.4	207	2.24	NB	207	2.29	NB	207	2.34	NB	203	2.31	NB	207	2.31	NB
-14.4	207	2.29	NB	207	2.34	NB	208	2.29	NB	207	2.29	NB	207	2.31	NB
-34.4	207	2.36	NB	204	2.34	NB	207	2.36	NB	208	2.64	NB	203	2.36	NB
-34.4															
-54.4	187	2.44	NB	192	2.38	NB	199	2.34	NB	182	2.39	NB	195	2.49	NB
-54.4	193	2.44	NB	192	2.38	NB	201	2.34	NB	189	2.29	NB	187	2.29	70
-74.4	181	2.44	NB	195	2.38	NB	179	2.29	70	193	2.49	NB	188	2.49	NB
-74.4	187	2.28	NB	192	2.34	75	177	2.29	70	183	2.39	NB	195	2.49	NB
-94.4	153	2.34	70	15	0.26	0	121	1.88	40	19	0.20	0	7	0.20	0
-94.4	177	2.24	70	137	2.04	70	92	1.42	30	15	0.31	0	15	0.15	0
-114.4	11	0.20	0	7	0.10	0	7	0.15	0	11	0.20	5	7	0.05	0
-114.4	24	0.30	0	13	0.26	0	29	0.41	0	15	0.15	0	19	0.30	0
-124.4															
-124.4															
-84.4	207	2.31	NB	144	2.16	30	128	2.03	25	167	2.36	50	172	2.34	40
-84.4				168	2.44	50				188	2.46	50	96	1.52	20
-104.4	208	2.39	NB	15	0.31	0	80	1.35	15	100	1.52	25	15	0.36	0
-104.4	128	2.06	25	24	0.41	5	91	1.45	20	15	0.25	0	13	0.23	0
-104.4										9	0.18	0			

NB: Not completely broken

TABLE 4: Mechanical Test Data for LT60 Steel (II)

THICKNESS: 63.5mm

SOURCE: ALGOMA STEEL CORP.

OUTER FIBRE STRAIN: 3% (B)

GRAIN SIZE: AVERAGE G.S.
= ASTM 8

MICROSTRUCTURE: FERRITE + PEARLITE

TENSILE TEST DATA (LONGITUDINAL)															
CONDITION	R			S			E			ES			EE		
YS(0.2%) MPa	406			376			377			441			357		
UTS MPa	519			525			538			525			529		
TOT. ELN. %	26.4			26.4			27.5			27.3			27.0		
UNI. ELN. %	15.5			15.5			13.3			14.6			13.3		
RA %	77.2			77.2			77.4			76.6			78.0		
IMPACT TEST DATA (LONGITUDINAL)															
Temp. °C	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %
26.7	204	2.49	NB	207	2.46	NB	203	2.49	NB	207	2.49	NB	208	2.49	NB
26.7															
5.6	208	2.34	NB	204	2.29	NB	204	2.41	NB	204	2.39	NB	207	2.24	NB
5.6	204	2.36	NB	207	2.41	NB	203	2.36	NB	204	2.31	NB	207	2.39	NB
-14.4	207	2.46	NB	204	2.39	NB	204	2.39	NB	208	2.34	NB	204	2.18	NB
-14.4															
-34.4	203	2.26	NB	203	2.16	NB	203	2.39	NB	207	2.39	NB	201	2.44	NB
-34.4	208	2.39	NB	201	2.39	NB	204	2.44	NB	208	2.24	NB	203	2.49	NB
-54.4	195	2.21	85	207	2.44	NB	195	2.39	80	188	2.29	NB	208	2.44	NB
-54.4	188	2.29	NB	112	1.63	30	208	2.29	NB	204	2.52	75	208	2.18	80
-74.4	207	2.49	NB	16	0.28	0	183	2.39	45	131	1.91	25	116	1.78	15
-74.4	143	2.03	30	123	1.96	25	113	1.91	20	161	2.41	30	187	2.46	40
-94.4	127	1.78	25	143	2.21	35	127	1.98	30	125	1.93	25	208	2.49	NB
-94.4	127	2.03	30	20	0.31	10	101	1.55	20	96	1.52	20	164	2.24	45
-94.4	77	1.25	10	13	0.31	0	21	0.33	0	11	0.23	0	11	0.23	0
-94.4													9	0.20	0
-104.4	7	0.15	0	7	0.10	0	9	0.25	0	7	0.13	0	9	0.23	0
-84.4	92	1.50	10	25	0.43	0	103	1.65	10	67	1.04	10	9	0.23	0
-84.4	108	1.70	20	13	0.23	5	208	2.46	NB	7	0.05	0	112	1.75	15
-104.4	9	0.15	0	11	0.23	0	5	0.10	0	13	0.36	0	11	0.20	0
-64.4	203	2.46	NB	163	2.34	40	133	1.88	20	184	2.39	60	143	2.11	30

NB: Not completely broken

TABLE 5: Mechanical Test Data for L160 Steel (III)

THICKNESS: 63.5mm

SOURCE: ALGOMA STEEL CORP.

OUTER FIBRE STRAIN: 6% (C)

GRAIN SIZE: AVERAGE G.S.
= ASTM 8

MICROSTRUCTURE: FERRITE + PEARLITE

TENSILE TEST DATA (LONGITUDINAL)															
CONDITION	R			S			E			ES			EE		
YS(0.2%) MPa	465			426			469			421			476		
UTS MPa	534			547			555			545			556		
TOT. ELN. %	25.2			26.0			22.8			24.6			19.9		
UNI. ELN. %	12.6			13.2			10.3			13.8			7.3		
RA %	76.7			75.0			75.8			75.4			76.7		
IMPACT TEST DATA (LONGITUDINAL)															
Temp. °C	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %	J	Lat. Expn mm	Shear %
26.7	208	2.21	NB	208	2.49	NB	208	2.18	NB	204	2.44	NB	208	2.29	75
26.7															
5.6	203	2.39	NB	215	2.36	NB	207	2.26	100	204	2.29	100	203	2.29	100
5.6	215	2.29	NB	207	2.08	NB	207	2.11	100	204	2.18	100	203	2.18	100
-14.4	207	2.39	NB	208	2.34	NB	203	2.31	80	201	2.36	80	201	2.36	80
-14.4															
-34.4	207	2.24	NB	181	2.16	80	213	2.11	80	113	1.75	15	127	1.85	20
-34.4	204	2.36	NB	199	2.06	80	151	2.16	40	167	2.29	NB	117	1.78	20
-54.4	148	2.01	70	125	1.85	35	192	2.24	75	125	1.85	30	113	1.63	30
-54.4	128	1.78	45	132	2.03	40	141	2.18	30	103	1.50	30	131	1.93	35
-74.4	80	1.37	5	19	0.33	0	7	0.10	0	92	1.47	5	47	0.71	0
-74.4	96	1.78	10	100	1.63	15	141	2.24	30	39	0.64	0	80	1.37	5
-94.4	13	0.18	5	7	0.18	10	15	0.33	5	96	1.52	15	16	0.31	5
-94.4	77	1.22	15	81	1.27	15	11	0.31	5	11	0.13	5	13	0.20	5
-94.4	7	0.13	0	11	0.23	0	9	0.15	0	9	0.23	0			
-94.4	7	0.36	0	7	0.13	0				7	0.13	0	9	0.20	0
-20.8													141	1.91	50
-84.4							11	0.15	0				152	2.18	50
-84.4	9	0.08	0	7	0.10	5	11	0.15	0	15	0.20	5	7	0.10	0
-104.4	9	0.18	5	7	0.18	0	11	0.15	0	11	0.18	0	7	0.13	0
-64.4	117	1.73	15	105	1.60	10	116	1.83	20	131	1.65	10	101	1.65	10
-74.4	113	1.78	20	35	0.56	5	9	0.13	0	15	0.33	0	9	0.13	5
-74.4	91	1.50	20	16	0.33	5	80	1.32	10	9	0.23	0	45	0.86	11

NB: Not completely broken

TABLE 6: Mechanical Test Data for A710 Gr A C1 3 Steel (I)

SOURCE: ENGINEERING METALS, HOUSTON, TEXAS

THICKNESS: 63mm

GRAIN SIZE: ASTM

OUTER FIBRE STRAIN: 0% (A)

MICROSTRUCTURE:

SPECIMEN ORIENTATION = TRANSVERSE
LONGITUDINAL

TENSILE TEST DATA															
CONDITION	R			S			E			ES			EE		
YS(0.2%)	585			557			556			594			561		
MPa															
UTS MPa	724			648			710			679			712		
TOT. ELN. %	18.8			20.1			17.0			19.0			19.2		
UNI. ELN. %	8.5			9.1			7.9			8.5			8.2		
RA %	77			80			78			79			79		
IMPACT TEST DATA															
Temp. °C	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %
26.7	190	1.94	60	177	2.44	NB	190	2.18	60	183	2.48	NB			
26.7	195	1.94	NB	170	2.50	NB	181	2.48	NB	179	2.44	NB			
5.6	186	2.14	60	183	2.24	NB	180	1.88	80	161	2.54	NB			
5.6	190	2.14	70				184	2.34	NB	174	2.50	NB			
-14.4	186	2.38	NB	195	2.60	NB	197	2.24	NB	181	1.55	NB	186	1.14	NB
-14.4	184	1.88	80	184	2.50	NB	186	2.38	NB	190	2.60	NB			
-34.4	152	1.82	15	175	2.54	NB	192	2.14	80	172	2.60	NB	192	1.94	NB
-34.4	186	1.82	70	188	2.34	NB	179	2.14	NB						
-44.4	170	1.68	60	183	2.44	NB	186	2.28	NB	156	2.54	NB	186	2.44	NB
-44.4	174	1.60	60	174	2.24	NB	188	2.04	NB	154	1.62	75	179	2.44	NB
-54.4	166	1.68	50	179	2.38	NB				175	2.54	NB	188	2.50	NB
-54.4	87	0.92	15	177	2.64	NB	188	2.24	NB	192	2.44	NB	38	0.50	30
-64.4	143	1.68	25	194	2.50	NB	181	2.14	50	168	2.54	NB	179	1.94	70
-64.4	141	1.72	40	181	2.30	NB	134	1.78	70						
-64.4	114	1.38	40	184	2.44	NB	188	2.04	75	174	2.34	NB	186	2.60	NB
-74.4	27	0.26	10	195	2.50	NB	188	2.04	80	179	2.54	NB	184	2.18	60
-74.4				195	2.28	NB				195	2.44	NB	163	1.94	60
-84.4	148	1.78	25				163	2.01	30	186	2.36	NB	83	1.09	5
-84.4	81	1.12	10										121	1.63	10
-94.4	14.5	0.25	0	104.9	1.52	20	136	1.85	20	165	2.26	40	137	1.80	10
-94.4							125	1.65	20	184	2.49	60	25	0.43	0
-104.4	10.9	0.05	0				62	0.41	0	188	1.22	NB	9	0.26	0
-104.4													16	0.28	0
-114.4				9	0.05	0	27	0.20	0	13	0.33	0	18	0.31	0
-114.4							24	0.15	0	11	0.13	0	15	0.33	0
-124.4				32.5	0.18	5							29	0.53	0
-124.4													18	0.31	0

NB: Not completely broken

TABLE 7: Mechanical Test Data for A710 Gr A C1 3 Steel (II)

SOURCE: ENGINEERING METALS, HOUSTON, TEXAS

THICKNESS: 63mm

GRAIN SIZE: ASTM

OUTER FIBRE STRAIN: 3% (B)

MICROSTRUCTURE:

SPECIMEN ORIENTATION = TRANSVERSE
LONGITUDINAL

TENSILE TEST DATA					
CONDITION	R	S	E	ES	EE
YS(0.2%) MPa	641	587	735	588	720
UTS MPa	699	656	785	660	771
TOT. ELN. %	18.6	20.4	14.0	20.5	17.7
UNI. ELN. %	5.5	8.0	4.2	8.3	5.2
RA %	74	79	77	80	77

IMPACT TEST DATA															
Temp. °C	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %
-26.7	186	2.08	90	175	2.54	NB	175	2.14	80	190	2.34	NB			
-26.7	186	2.04	NB	174	2.50	NB	175	2.04	80	179	2.50	NB			
										177	2.50	NB			
-5.6	168	2.28	NB	183	2.44	NB	177	2.24	NB	183	2.54	NB			
-5.6	170	1.82	80	186	2.44	NB	192	2.14	80						
-14.4	184	1.78	85	186	2.54	NB	181	1.82	80	190	2.54	NB	172	1.82	75
-14.4	183	2.14	85	183	2.44	NB	184	2.34	70	190	2.54	NB			
-34.4	170	1.78	80	195	2.50	NB	188	2.14	NB	193	2.44	NB			
-34.4	145	1.62	60	183	2.38	NB	168	1.94	60	179	2.50	NB	51	0.86	20
-44.4	121	1.42	50	192	2.64	NB	150	1.82	50	177	2.38	NB	154	1.72	60
	51	0.86	20												
-44.4	119	1.42	80	184	2.60	NB	130	1.52	30	184	2.50	NB	148	1.72	50
							184	1.78	50						
-54.4	137	1.58	40	188	2.28	NB				184	2.44	NB	18	0.30	10
-54.4	42	0.62	10	186	2.34	NB	150	1.94	50-60	183	2.54	NB	119	1.48	40
-64.4	25	0.30	10	192	2.24	NB	134	1.69	60	170	2.38	NB	25	0.40	5
							156	1.58	40						
-64.4	20	0.30	10	184	2.38	NB	25	0.30	10	173	2.38	NB			
-74.4	16	0.20	10	186	2.38	NB	20	0.20	0	195	2.44	NB	33	0.50	10
-74.4				184	2.44	NB				186	2.54	NB	20	0.20	0-5
-84.4				166	2.24	40				183	2.44	NB			
-84.4															
-94.4				166	2.29	40				181	2.18	50			
-94.4				190	2.34	50				119	1.73	20			
-104.4				145	1.02	40				18	0.17%	0			
-104.4															
-114.4				112	0.81	40				15	0.08	0			
-114.4				11	0.13	0				22	0.10	0			
-124.4															
-124.4															
-114.4				29	0.41	0									
-119.4															

NB: Not Completely Broken

TABLE 8: Mechanical Test Data for A710 Gr A C1 3 Steel (III)

SOURCE: ENGINEERING METALS, HOUSTON, TEXAS

THICKNESS: 63mm

GRAIN SIZE: ASTM

OUTER FIBRE STRAIN: 5.5% (C)

MICROSTRUCTURE:

SPECIMEN ORIENTATION = TRANSVERSE
LONGITUDINAL

TENSILE TEST DATA															
CONDITION	R			S			E			ES			EE		
YS(0.2%) MPa	728			614			742			586			765		
UTS MPa	140			683			781			649			800		
TOT. ELN. %	14.2			18.8			15.7			21.9			14.9		
UNI. ELN. %	2.13			7.9			4.5			8.2			4.0		
RA %	74			80			75			76			79		
IMPACT TEST DATA															
Temp. °C	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %	J	Expn mm	Shear %
26.7	190	2.18	60	190	2.24	NB	190	2.14	70	193	2.18	NB			
26.7	188	2.18	60	188	2.18	NB	192	2.14	80	174	2.54	NB			
5.6	186	2.14	70	188	2.44	NB	174	1.72	80	181	2.50	NB			
5.6	188	2.24	85	188	2.24	NB	186	1.94	85						
-14.4	168	1.94	60	192	2.38	NB	146	1.72	70	197	2.50	NB	148	1.78	80
-14.4	163	1.78	60	192	2.38	NB	125	1.42	40	159	2.50	NB			
-14.4							194	2.18	90	186	2.38	NB			
-34.4	67	1.06	15	195	2.38	NB	137	1.68	80	188	2.50	NB	132	1.62	50
-34.4	146	1.92	70	175	2.28	NB				186	2.38	NB	80	1.02	20
-44.4	74	1.12	20	186	2.24	NB	110	1.48	50	177	2.50	NB	38	0.56	10
-44.4	47	0.66	15	190	2.24	NB	18	0.30	0-5	175	2.50	NB			
-44.4							121	1.48	50						
-44.4							184	1.78	50						
-54.4	29	0.30	10	177	2.08	60				175	2.50	NB	25	0.40	10
-54.4	34	0.56	15	193	2.34	NB	36	0.46	0-5	177	2.44	NB	43	0.60	10
-64.4	12.7	0.26	5	184	2.28	NB	18	0.16	0-5	177	2.24	NB	4	0.10	10
-64.4	14.5	0.16	5	192	2.50	80	15	0.26	0-5	175	2.18	NB	18	0.26	5-10
-74.4	5.4	0.10	5	188	2.28	NB	25	0.20	10	188	2.50	NB	11	0.16	5
-74.4	13	0.16	10	174	2.18	65	15	0.20	0-5	190	2.18	70	1		
-84.4				118	1.75	30				163	2.24	40			
-84.4															
-94.4				119	1.68	25				134	1.85	40			
-94.4				105	1.52	20				123	1.70	20			
-104.4				112	0.76	40				166	1.09	40			
-104.4															
-114.4				20	0.41	10				47	0.91	30			
-114.4				54	0.13	5				132	0.91	10			
-124.4				13	0.18	0				34	0.20	0			
-124.4															
-120.4										25	0.15	0			
-114.4				9	0.08	0									

NB: Not completely broken

TABLE 9: The Transverse Charpy Results for LT60 Steel.

TRANSVERSE CHARPY RESULTS

Temp., °C	OJAR			OICR			OICES		
	CVN J	Lat. Exp. mm	Shear %	CVN J	Lat. Exp. mm	Shear %	CVN J	Lat. Exp. mm	Shear %
-114.4	9	0.13	0						
-114.4	36	0.58	0						
-104.4	5	0.10	0						
-104.4	15	0.15	0						
-94.4	56	0.71	5	72	1.07	10	9	0.13	0
-94.4	--	--	--	16	1.08	0	--	--	--
-84.4	58	0.86	5	--	--	--	11	0.13	0
-84.4	--	--	--	--	--	--	--	--	--
-74.4	85	1.27	20	62	0.94	10	13	0.15	0
-74.4	110	1.63	30	51	0.79	10	9	0.13	0
-64.4				--	--	--	83	1.32	20
-64.4				--	--	--	87	1.37	20
-54.4				71	1.07	10	13	0.20	0
-54.4				--	--	--	25	0.36	0
-44.4				--	--	--	74	1.14	20
-44.4				--	--	--	--	--	--
-34.4				71	0.99	20	92	1.14	20
-34.4				89	1.27	20	85	1.32	20
-14.4				116	1.52	40	109	1.22	40
-14.4				--	--	--	--	--	--

TABLE 10: CTOD Fracture Toughness Test Report (I)

Specimen Code or Standard: BS 5762-1979

Specimen Type: BxB

Specimen Materials: LT60 Steel

Specimen Size: ~ 36x36x190 mm

Sp. No.	Test Temp. °C	a _{avg.} mm	B mm	W mm	Y	σ_y MPa	V _f mm	P _{max} kg	$\delta m(\delta u)$ mm
01AR #1	-60	18.21	35.48	35.46	11.09	342	2.903	6,131	0.787
01AR #2	-60	17.88	35.48	35.51	10.73	342	4.999	6,897	1.361
01AR #3	-60	18.03	35.43	35.46	10.91	342	4.778	6,795	(1.285)
01BR #1	-60	17.30	35.15	35.13	10.36	406	4.359	7,204	1.232
01BR #2	-60	17.58	35.48	35.51	10.44	406	4.999	7,459	1.400
01BR #3	-60	17.65	35.51	35.46	10.54	406	4.737	7,439	1.321
01CR #1	-60	16.99	35.13	35.13	10.08	465	3.998	7,817	(1.171)
01CR #2	-60	17.76	35.46	35.51	10.61	465	3.858	7,613	1.087
01CR #3	-60	17.98	35.54	35.48	10.85	465	4.999	7,357	1.359

TABLE 11: CTOD Fracture Toughness Test Report (II)

Specimen Code or Standard: BS 5762-1979

Specimen Type: BxB

Specimen Materials: LT60 Steel

Specimen Size: ~ 36x36x190 mm

Sp. No.	Test Temp. °C	a _{avg.} mm	B mm	W mm	Y	σ_y MPa	V _f mm	P _{max} kg	$\delta m(\delta u)$ mm
01CS #1	-60	17.32	35.48	35.51	10.21	426	2.611	7,408	(0.775)
01CS #2	-60	18.96	35.46	35.51	10.81	426	1.920	6,591	(0.556)
01CS #3	-60	17.09	35.48	35.51	10.01	426	1.161	6,826	(0.376)
01CES #1	-60	18.11	35.56	35.48	10.97	421	1.560	6,386	(0.455)
01CES #2	-60	17.86	35.51	35.48	10.72	421	2.019	7,230	(0.597)
01CES #3	-60	17.70	35.51	35.51	10.56	421	0.361	5,743	(0.140)
01CEE #1	-60	17.48	35.51	35.48	10.36	476	1.260	7,281	(0.406)
01CEE#2	-60	17.15	35.10	35.23	10.17	476	0.800	6,795	(0.277)
01CEE #3	-60	17.65	35.15	35.18	10.67	476	0.480	6,284	(0.180)

TABLE 12: CTOD Fracture Toughness Test Report (I)

Specimen Code or Standard: BS 5762-1979

Specimen Type: BxB

Specimen Materials: A710 Gr A C1 3

Specimen Size: ~ 36x36x190 mm

Sp. No.	Test Temp. °C	a _{avg.} mm	B mm	W mm	Y	σ_y MPa	V _f mm	P _{max} kg	$\delta m(\delta u)$ mm
02AR #1	-60	21.4	35.9	35.9	14.74	585	0.4495	5,804	(0.152)
02AR #2	-60	20.4	35.9	35.9	13.32	585	0.41148	6,110	(0.147)
02AR #3	-50	20.9	36.0	36.0	14.03	585	0.3810	5,569	(0.132)
02BR #1	-60	18.7	36.0	36.0	11.25	641	0.1651	6,437	(0.081)
02BR #2	-50	18.6	35.9	36.0	11.27	641	0.050	4,884	0.038*
02BR #3	-50	18.8	35.9	36.0	11.41	641	0.180	5,528	(0.079)
02CR #1	-60	19.4	36.0	36.0	12.04	728	0.0254	4,777	0.036*
02CR #2	-50	19.0	35.9	36.0	11.63	728	0.0406	5,007	0.041*
02CR #3	-50	18.9	35.9	36.0	11.56	728	0.0381	6,233	0.076*

TABLE 13: CTOD Fracture Toughness Test Report (II)

Specimen Code or Standard: BS 5762-1979

Specimen Type: BxB

Specimen Materials: LT60 Steel

Specimen Size: ~ 36x36x190 mm

Sp. No.	Test Temp. °C	a _{avg.} mm	B mm	W mm	Y	σ_y MPa	V _f mm	P _{max} kg	$\delta m(\delta u)$ mm
02CS #1	-60	19.1	35.8	36.0	11.74	614	0.439	7,677	(0.178)
02CS #2	-60	19.4	35.9	36.0	12.06	614	0.020	5,155	0.038*
02CS #3	-50	19.6	36.0	36.0	12.37	614	2.192	7,714	0.582
02CEE #1	-60	19.1	35.9	36.0	11.76	765	0.000	3,730	0.0178*
02CEE #2	-50	19.0	35.9	35.9	11.66	765	0.000	3,679	0.015*
02CEE #3	-50	19.2	35.9	36.0	11.91	765	0.000	4,373	0.023*
02CES #1	-60	19.1	36.0	35.9	11.76	586	1.552**	8.272	0.455**
02CES #2	-60	19.5	35.8	35.9	12.19	586	0.020	5,036	0.038*
02CES #3	-60	19.2	35.9	36.0	11.90	586	1.402	7,766	(0.406)

* Designates δ behaviour.

** Test stopped to avoid damage to clip gauge - Load still increasing at a significant rate.

TABLE 14: CTOD Fracture Toughness Test Report (III)

Specimen Code or Standard: BS 5762-1979

Specimen Type: BxB

Specimen Materials: LT60 Steel

Specimen Size: ~ 36x36x190 mm

[illegible]

PART B: "AN INVESTIGATION INTO THE WELDABILITY OF TWO CANDIDATE STEELS"

by S. Pond

1. INTRODUCTION

The discovery of offshore oil and gas in Canadian coastal waters has created a need to extend the limits of present material and welding technology. Design temperatures which could be in the order of -30 to -60°C have made it necessary to improve upon the properties of materials such as normalized BS 4360 Gr. 50 D steel, presently used in the North Sea where the minimum design temperature is -10°C.

Clean, low carbon steels with small amounts of grain refining elements are being used, in an effort to produce tough steels with improved weldability. The low levels of carbon lead to better weldability and less demanding preheat requirements, while the microalloying elements are used to meet toughness and strength requirements, although it is believed that certain microalloying elements in large amounts may be detrimental to toughness in the heat affected zone (HAZ). In addition, steels are being improved by using heat treatments such as on-line accelerated cooling, quenching and tempering, and precipitation hardening. One such steel is ASTM A710 Gr. A, Cl. 3 which is a precipitation hardened, low carbon, Cu-Ni-Nb steel. This steel was designed initially for use in Arctic environments and is believed to have made significant

in-roads in Navy ship applications. It is natural that it be a candidate for use in Canadian offshore and Arctic applications.

With a view to promote the use of Canadian resources utilized in offshore development, Algoma Steel Corporation made a special heat of steel with the aim of meeting Lloyds LT 60 specification requirements in thicknesses up to 75 mm. This steel conforms to CSA G40.21 Gr. 350 WT specification as well and is similar to BS 4360 Gr. 50 D which is commonly used in North Sea applications.

Steel types ASTM A710 Gr. A, Cl. 3 (from Armco Inc.) and Lloyds LT 60 (from Algoma Steel Corp. Ltd.) are two potential steels for use in Arctic and offshore applications, both of which could be produced in Canada. These have been examined in the present study from the point of view of susceptibility to hydrogen induced cold cracking. Steel to the specification of BS 4360 Gr. 50 E, has been included in the program as a reference steel. BS 4360 Gr. 50 E has the same general chemical composition as Gr. 50 D but is required to meet 27J @ -50°C as opposed to 27J @ -30°C for Gr. 50 D. Both have been used for critical sections in offshore structures in the North Sea.

1.1 Hydrogen Induced Cold Cracking

Cold cracking can occur both in the weld metal and the HAZ. The primary factors influencing the incidence of cold cracking are:

susceptibility of microstructure to hydrogen embrittlement (related to chemical composition and cooling rate), the hydrogen content of the deposited metal, the stress or strain levels at the point of crack initiation (level of restraint) and the temperature. In certain situations, one of the factors may dominate over others. For example, under conditions of stress and high hydrogen, cold cracking may occur in a relatively nonsusceptible microstructure.⁽¹⁾

In view of the above fundamental factors contributing to the incidence of cold cracking, welding procedural variables (welding process, consumable, preheat, etc.) become very important in the control of this defect. Preheat is used to alter the cooling rate of a welded joint which, in the lower temperature range, is important in controlling the amount of hydrogen retained in the weld at temperatures at which cracking could occur. Higher heat inputs promote the presence of softer, less susceptible microstructures, and the weld process and consumable selection affects the amount of hydrogen that is introduced into the weld zone.

1.2 Tests to Assess Cold Cracking Susceptibility

In production welding, the incidence of cold cracking in joints is reduced by using low hydrogen processes and by controlling heat input, preheat and post weld heat treatment to allow hydrogen to diffuse from the weld metal and to produce less susceptible microstructures.

In tests for comparative assessment of cold cracking susceptibility of steels, arbitrary values of hydrogen, heat input and restraint are chosen, generally to represent the 'worst' condition and the extent of cracking measured as a function of preheat. Preheat required to give no cracking is expected to depend predominantly on the chemical composition and microstructure of the base material, all other relevant variables having been kept constant.

Various comparative tests have been devised to evaluate the cold cracking susceptibility of the HAZ. Of these tests, two which have been used extensively are the controlled thermal severity (CTS) test⁽²⁾ and the Tekken Y-groove test.⁽⁷⁾ The former provides the basis for preheat requirements in various British codes, and the latter provides the same for Japanese codes.^(3,4) There is a significant amount of North American experience as well with these tests (for example, see Reference 5). The underlying approach for the two tests is different, with the CTS test being based on relatively low restraint fillet welds, and the Tekken test on a more highly restrained weld bead in a groove joint.

Hardening curves are established quite easily and provide an indirect indication of cold cracking susceptibility on the basis of the maximum hardness to be expected in the HAZ as a function of heat input. Such information is useful since many fabrication

specifications provide maximum hardness criterion to avoid cold cracking as well as stress corrosion cracking.

The implant test is an applied stress test used to determine the lower critical stress to avoid hydrogen cold cracking. This is a small scale test, the results of which are thought to bear a direct relationship to those obtained in large scale rigid restraint cracking (RRC) and tensile restraint cracking (TRC) tests.⁽⁶⁾

In the weldability study described in the following sections, the above mentioned tests have been used to assess the HAZ cold cracking susceptibility of the two main steels and the reference steel.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

2.1.1 Steels

Heat affected zone hardening behaviour and weldability tests have been performed for the following three steels:

- | | | |
|----|------------------|-----------------------------|
| 1) | A710 Gr. A, Cl 3 | 76 mm (Armco Inc.) |
| 2) | Lloyds LT 60 | 63 mm (Algoma Steel Corp.) |
| 3) | BS 4360 Gr. 50 E | 50 mm (British Steel Corp.) |

Chemical compositions of the three steels are listed in Table 1 and mechanical properties are shown in Table 2.

2.1.2 Consumables

(a) Consumables for Hardening Curves

Lincoln L61 wire (1.8 and 3.8 mm dia.) with Lincoln 860 flux.

Linde 86 wire (.89 mm dia.) with Linde 85 flux.

(b) Consumables for Tekken Test

Linde 86 wire (1.14 mm) with Argon/10% CO₂ gas for restraint welds.

Lincoln Fleetweld 5P E6010 (3.8 mm)

Lincoln Jetweld LH78 E7018 (3.8 mm)

Arcweld 312 E7016 (3.8 mm)

Lincoln Jetweld LH E8018-C1 (3.8 mm)

CLA Atom Arc E11018 (3.8 mm)

(c) Consumables for CTS Test

Linde 86 wire (1.14 mm) with Argon/10% CO₂ gas for anchor welds.

Lincoln Jetweld LH78 E7018 (3.8 mm)

Arcweld 312 E7016 (3.8 mm)

Lincoln Jetweld LH E8018-C1 (3.8 mm)

(d) Consumables for Implant Test

Lincoln Jetweld LH E8018-C1 (3.8 mm)

2.2 Weldability Tests

2.2.1 Hardening Curves

Two full thickness plates, 356 mm by 100 mm were cut for each steel with the 356 mm side parallel to the rolling direction. 100 mm long run-on and run-off tabs were tack welded to the test pieces. Operating conditions for the nine bead on plate welds are given in Table 3.

Cooling curves were recorded as mV vs. time on a Sargent Welch X:Y strip chart recorder connected through an Omega-CJ cold junction compensator to a harpoon type Pt/13%Rh, Pt thermocouple. The thermocouple was manually plunged into the weld pool directly behind the arc and cooling cycle monitored until the temperature fell below 100°C.

One half of each bead was stress relieved at 620°C for two hours, and furnace cooled. The other half was examined in the as welded condition.

Examination

Subsequent to heat treatment, both the stress relieved and as welded beads were sectioned in three places in order to take hardness measurements in several areas of the heat affected zone (HAZ).

The HAZ does not have uniform hardness or microstructure. Hardness is generally thought to be at a maximum in the concave portion of the HAZ close to the fusion boundary which is the region of coarsest austenite grain size.

Five Vickers (10 kg load) hardness readings were taken on each section close to the fusion boundary as shown in Figure 1. The average of the two highest readings from each section yielded the mean maximum hardness values used in the hardening curves.

Metallography

The bead on plate welds were used to study the microstructure of the HAZ at various heat inputs. A section for each heat input was polished and etched using 4% picral followed by 2% nital. Austenite grain size measurements were obtained using an austenite grain size screen.

2.2.2 Tekken Test

Test Block Preparation

The test pieces were designed on the basis of Japanese standard JIS Z 3158.⁽⁷⁾ The Tekken test is a high restraint test in which the restraint is self-imposed and dependent on the geometry of the test piece. The oblique y-groove used is the configuration accepted in Japan for testing heat affected zone (base metal) susceptibility to hydrogen cracking. The dimensions of the test pieces are shown in Figure 2. Photographs of the actual test set-up are shown in Appendix B1. Restraint welds were deposited in 60° double V-grooves. Welding parameters for these welds are also listed in Appendix B1. In an attempt to maintain a 2 mm gap, a shim plate, 2 mm in thickness, was inserted into the groove.

Procedure

A list of hydrogen and preheat levels used in the tests is given in Table 4. Essentially, there are two hydrogen levels: low hydrogen, obtained by baking electrodes for one hour at 450°C and holding at 120°C until use, and high hydrogen, obtained by exposing baked electrodes to 90% humidity for 16 to 24 hours in a humidity cabinet.

After the initial testing had been completed it was realized that the root gap in the Tekken test may have a significant effect on the type of cracking obtained. Additional tests were carried out using a 3 mm shim plate to ensure a 2 mm gap after restraint welding.

The prepared blocks were heated in a Park thermal annealing box furnace to approximately 10°C above the selected preheat temperatures and removed from the furnace. Once the desired preheat was reached in the test block, one weld bead was laid in the groove. For low temperature tests, an insulated container was filled with dry ice. Test pieces which had been pre-cooled to -10°C in a freezer were packed in the dry ice. Once the test blocks reached 10°C below the selected temperature, the block was removed from the ice and welded immediately. A heat input of 1.7 kJ/mm was used for the test weld and welding parameters for the test welds are listed in Appendix B1.

Weld metal hydrogen measurements were carried out using the ISO 3690 mercury method.

Examination

After welding, test pieces were left for 48 hours at room temperature to ensure sufficient time for hydrogen diffusion and cracking to occur. After this time, the test welds were cut into five sections which were ground to 600 grit and examined for cracks. Pieces were then etched with 10% nital for photographing. Dye penetrant check was used when there were no visible cracks. A Zeiss Videoplan Image Analyzer system was used to measure the extent of the weld and HAZ cracking.

2.2.3 Controlled Thermal Severity (CTS) Test

Test Block Preparation

This test has no established standard, however, it is widely used in various modified forms. In this study, CTS test blocks have been designed on the basis of a procedure established at the Welding Institute.⁽²⁾ This is a self restraining test in which two single pass fillet welds may be assessed on one test piece. The dimensions of the CTS test blocks are shown in Figure 3.

Welding parameters for the 13 mm fillet anchor welds were the same as for the Tekken test restraint welds shown in Appendix B1. The bolt was tightened to a torque of 100 Nm before anchor welding and retightened after anchor welds were laid.

Procedure

Hydrogen and preheat levels tested are listed in Table 5. Hydrogen and preheat levels were obtained using the method described for the Tekken test. Once cooled to the selected preheat level, a test bead was placed on one side of the test block and 48 hours allowed to elapse before welding the second test bead on the opposite side. Welding parameters for the test welds are the same as those for the Tekken test welds shown in Appendix B1.

During welding, a Pt/13% Rh, Pt thermocouple was manually plunged into the weld pool directly behind the arc. The time-temperature

cooling curves were monitored using a Sargent Welch X:Y strip chart recorder as in the hardening curve test.

Examination

A period of 48 hours was allowed to elapse prior to sectioning of the test welds.

Both test welds were then cut into six sections, ground to 600 grit and examined for cracks. Subsequently they were etched with 10% nital for photographing. Once again, dye penetrant was used when there were no visible cracks. A Zeiss Videoplan Image Analyzer was used to measure the extent of cracking where it was observed.

2.2.4 Implant Test

Implant and Backing Plate Preparation

The test pieces were made to the specification used by the Department of Energy, Mines and Resources^(8,23) and tests were carried out at CANMET/PMRL. This test is used to assess cold cracking susceptibility in the HAZ of weldments by measuring the lower critical stress of the material. The test uses a cylindrical implant which has a helical notch at one end. The implant is inserted into a hole drilled in a backing plate, such that the notched end is flush with the plate surface. The dimensions of the implant and backing plate are shown in Figure 4. Photographs of the test apparatus are shown in Appendix B1.

Procedure

The variable in this test was the applied stress, all other parameters were held constant as shown in Table 6.

A single bead on plate at a heat input of 1.7 kJ/mm was placed on the backing plate, passing over the implant. Two minutes after welding, the bead was quenched for four minutes. The implant was then set up in a modified creep testing machine and two minutes after quenching the implant was loaded. Once the appropriate load was applied a timer was started which would shut off automatically if the specimen broke. The test was terminated after 1000 minutes if the implant had not ruptured.

The steel A710 was also implant tested at the Welding Institute of Canada. Test conditions were the same with the exception that lower hydrogen levels were used at WIC.

Examination

Several implants chosen at random were sectioned in half to establish whether cracking had occurred in the HAZ. The sections were mounted, polished and etched with 2% nital. Vickers 10 kg load hardness measurements were taken in the HAZ of the implant and backing plate.

3. RESULTS

3.1 Hardening Curves

The hardening curves for both the as welded and stress relieved conditions are shown in Figures 5 and 6. These curves have been plotted as mean maximum HAZ hardness versus cooling time from 800 to 500°C, as cooling time can be measured more accurately than cooling rate. Thermal cycle data for the nine heat inputs are summarized in Table 3. For the three thicknesses studied, variations in cooling times were small. For this reason, average values for the three steels are shown in the table.

The HAZ photomicrographs corresponding to each heat input are shown in Figures 7 through 12.

3.2 Tekken Test

The most important results obtained in the Tekken tests are shown in Table 7. More complete tables of results may be found in Appendix B2.

The effect of root gap in steel BS 4360 Gr. 50 E is shown in Figure 13 which illustrates the different types of cracking obtained. Typical weld metal and HAZ cracks found in the Tekken tests are shown in Figure 14.

3.3 CTS Test

CTS test results are summarized in Table 8. As with the Tekken tests, more complete tables of results may be found in Appendix B2.

Typical weld metal and HAZ cracks found in these tests are shown in Figures 15 and 16.

3.4 Implant Test

Implant test results are generally presented as stress vs time to rupture. This curve is shown in Figure 17. Results from implant tests carried out at WIC are also included. Typical HAZ cracks found in ruptured implants are shown in Figure 18.

4. OBSERVATIONS AND DISCUSSION

4.1 Hardening Curves

When examining hardening curves, the three features of importance are: the maximum hardness, slope and position of the curves. For any given critical hardness level to avoid cold cracking, the curves also yield the corresponding minimum cooling time between 800° and 500°C. This gives some indication of the minimum heat input allowable if one does not wish to exceed the chosen hardness. The maximum hardness plateaus seen in the hardening curves indicate the maximum HAZ hardness achievable, independent of the welding process. The magnitude of the plateau is dependent mainly on carbon content.^(9,10) This relationship is illustrated in Figure 19 which shows a good correlation between carbon content and the value of the maximum hardness plateau. The maximum hardness curve from Burns, Moore and Archer⁽¹⁰⁾ has also been included in this Figure for comparison. Alloying elements are thought to change only the critical cooling rate at which this hardness is achieved, not the level of maximum hardness.⁽¹⁾ Elements which increase hardenability tend to shift the hardening curve towards the right. In addition, the effects of microalloying elements tend to be small at high cooling rates, increasing as cooling rates decrease.

From the hardening curves in Figure 5, it is apparent that the curve for steel A710 Gr. A, Cl. 3 has much lower slope and a

lower maximum hardness than the other two. This leads to a wider range of acceptable welding parameters which, in turn, implies better weldability. Generally 300-350 HV₁₀ is considered the range of hardness above which cold cracking susceptibility may become a problem. Even as quenched, steel A710 Gr. A, Cl. 3 did not harden much above 350 HV₁₀ due to the low level of carbon. Figure 20 shows the critical cooling time from 800 to 500°C at a hardness of 300 HV₁₀ for all three steels.

Relating Figures 7 through 12 with the hardening curves, the sequence of microstructures appear to agree well with the measured hardnesses. The HAZ of steels BS 4360 and Lloyds LT 60 are similar. The structures are predominantly martensitic at the highest cooling rate. Martensite is gradually replaced with increasing amounts of bainite as the cooling rate decreases. Initially, bainite is present as parallel laths, but it becomes coarser and more randomly oriented as cooling time increases. The carbon rich regions in the bainitic structure are now known as aligned martensite-austenite-carbide constituent (M-A-C) after Abson and Dolby,⁽¹¹⁾ which denotes ferrite containing martensite, retained austenite or carbide phases. This includes ferrite side plates, upper and feathery bainite and lamellar product.

The structure in the HAZ of A710 steel is similar to that of the other two, with some exceptions. There is less martensite present and the M-A-C coarsens to a much greater extent, although prior austenite grain size in the coarse grained region of the HAZ is similar for all three steels at any given heat input. There is also an appreciable quantity of grain boundary ferrite for Lloyds LT 60 and BS 4360 steels at high heat inputs, while there does not appear to be any grain boundary ferrite in the A710 material. Grain boundary ferrite is present in the HAZ of these steels at the position on the hardening curves where the hardness of A710 Gr. A, Cl. 3 levels off. At this point, the hardnesses of the other two steels drop to less than that of the A710 steel.

The hardening curves in Figure 6 show the effects of stress relief heat treatment at 620°C. The decrease in hardness reflects the tempering effect and indicates that considerable substructural changes such as the dissipation of internal stresses and a decrease in dislocation density have occurred. The microstructures also show subtle changes as shown in Figures 8, 10, and 12. The carbides appear to be coalescing to a certain extent in the tempered structure.⁽¹²⁾ The hardness levels after stress relieving appear to correspond with those obtained after welding at very high heat input, with the A710 material softening to a lesser extent than the other two. This could be due to the precipitation

of copper or niobium carbides in the HAZ of A710, since the stress relieving temperature lies within the precipitation hardening range of 540 to 665°C.

Summarizing the results of the hardening curve test; A710 Gr. A, Cl. 3 with .05% carbon shows the lowest HAZ hardness, Lloyds LT 60 with .12% carbon follows and BS 4360 Gr. 50 E with .16% carbon has relatively the highest HAZ hardness.

4.2 Tekken Tests

The Y-groove Tekken test is a high restraint test intended to evaluate HAZ hydrogen cold cracking susceptibility. It is common in such tests to use a weld metal deposit having mechanical properties comparable to that of the base material. When weld metal cracking occurs, strain on the HAZ is effectively reduced so that true HAZ cracking characteristics cannot be obtained. In light of this, it is difficult to assess the results of the Tekken tests due to the high percentage of weld metal cracking which occurred, however, it is not unusual to obtain predominantly weld metal cracking in the Y-groove test.⁽¹³⁾

Several different types of electrodes were used in an effort to have a weld metal which could withstand the high restraint. Table 4, showing conditions tested includes the electrode types used. For

steel BS 4360 Gr. 50 E, E7018 and E7016 electrodes were chosen for the test welds on the basis of composition and tensile strength. At room temperature with low hydrogen there was neither HAZ nor weld metal cracking. With increased levels of hydrogen, weld metal cracking occurred. It would appear that even though the weld metal strength was similar to that of the base material, under such conditions of restraint, hydrogen and preheat, the WM microstructure was still more susceptible.

The A710 material has higher strength than the BS 4360 steel. To match strength and composition, E8018-C1 electrodes were chosen for the test welds in the A710 steel.

In this case at room temperature, even at low levels of hydrogen, weld metal cracking was observed. This could be due to the slightly higher level of restraint caused by the additional 13 mm thickness. In the past the assumption has been made that above 40 mm restraint becomes constant,⁽¹⁴⁾ however, more recent papers have suggested formulas for calculating restraint at greater thicknesses.^(15,16) Employing electrodes for lower and higher weld metal strengths (E7018, E6010 and E11018) failed to prevent cracking in the weld metal; no cracking in the HAZ was observed. It is possible that dilution effects from the more highly alloyed A710 steel make the WM more susceptible. The results however, suggest that preheat

requirements in the welding of A710 steel would be governed by the need to avoid cold cracks in the weld metal rather than in the HAZ.

After carrying out many of the tests, it was discovered that some of the root gaps were less than the specified 2 mm. Due to observations by Campbell⁽⁵⁾ that a change in gap size could change the type of cracking, some tests were carried out using a well controlled gap size of 2 mm and a hydrogen level of 12-14 ml/100g of deposited weld. This appeared to affect only the type of cracking seen in steel BS 4360. HAZ cracks were observed at room temperature but not at a preheat of 50°C in this steel. However, weld metal cracking was still present in A710 Gr. A, Cl. 3 steel and no cracking at all was seen in Lloyds LT 60 at room temperature. These additional results tend to reinforce the idea that steel A710 Gr. A, Cl. 3 is virtually unsusceptible to HAZ hydrogen cold cracking under the conditions tested.

Summarizing the results of the Tekken tests; steel A710 Gr. A, Cl. 3 has the lowest susceptibility to HAZ cracking and hence the best weldability. Lloyds LT 60 shows a critical preheat level less than room temperature and the BS 4360 Gr. 50 E steel has a critical preheat level between 20° and 50°C.

4.3 CTS Tests

Very little cracking at all was found in this test. Once again some weld metal cracking was observed for the A710 material. At low temperatures (-30°C) and high levels of hydrogen, HAZ cracks were observed for steels BS 4360 and Lloyds LT 60, while no cracks at all were found in steel A710. These results show good correlation with those found in the controlled gap Tekken tests, although critical preheat levels are slightly lower in the CTS tests. This is not unexpected since the CTS test has a lower level of restraint than the Tekken test.

Summarizing the results of the CTS tests; steel A710 Gr. A, Cl. 3 has the lowest susceptibility to HAZ cracking with a critical preheat level less than -30°C . Lloyds LT 60 and BS 4360 Gr. 50 E steels both show a critical preheat level between -30°C and room temperature.

4.4 Implant Tests

At first glance, the implant tests seem to rate the weldability of the steels quite differently from the other tests. As expected, in the curve of lower critical stress vs time to rupture (Figure 17), steel A710 shows the highest value for the lower critical stress (LCS). However, BS 4360 steel shows a LCS comparable to that of A710 while the LCS for Lloyds LT 60 has a much lower value.

It has been suggested by Hart⁽¹⁸⁾ that the use of the implant test as a substitute for the CTS test is potentially limited, mainly due to the fact that transformation stresses and strains are lower for higher carbon equivalent (lower transformation temperature) steels. However, the M_s (martensite start) temperatures for the three steels, calculated using an equation relating M_s temperature to chemical composition,⁽²²⁾ are quite close together. In the absence of more specific data, this suggests that differences in transformation temperature and therefore stresses would be relatively minor for the three steels. Consequently, it does not explain the apparent anomaly in the ranking of the three steels.

In an applied stress test, an inherent strength difference either in the base material or in the HAZ may play an important role in the performance of the materials tested. Since the steels have effectively been heat treated to different strength levels in the HAZ due to welding, it was considered more meaningful to normalize the lower critical stress with respect to an estimated strength of the HAZ based on hardness in the implants. Since the relationship between hardness and yield strength has not been well established, tensile strength was used. This was estimated using conversions found in the ASM Metals Handbook.⁽¹⁹⁾ Figure 21 shows the ratio of lower critical stress to "apparent" tensile strength vs. the time to rupture. In this case A710 has the highest ratio, while BS

4360 and Lloyds LT 60 steels are rated very closely and within experimental error, could be said to have the same ratio.

One set of implant tests were also carried out on the A710 material at the Welding Institute of Canada. Test conditions were identical to those used in the present study with the exception of a considerably lower hydrogen level. Instead of 15-20 ml/100g, the WIC tests had only 5-8 ml/100g. Hydrogen levels can have a dramatic effect on the lower critical stress of a material.⁽²⁰⁾ For this reason the variation in results seen in Figure 17 is not unusual.

Summarizing the results of the implant tests; the stress vs. rupture time curve normally used to assess weldability in the implant test, does not yield results entirely consistent with the other tests performed. By plotting the critical stress as a percentage of the apparent tensile strength in the HAZ, the results become more in line with those found in the CTS test with A710 having the best weldability and BS 4360 and Lloyds LT 60 steels having weldability similar to each other.

4.5 Carbon Equivalent Formulae and Weldability

The use of carbon equivalent to assess weldability of steels has become increasingly common over the last two decades, higher carbon equivalent implying poor weldability. Until recently, the IIW carbon equivalent formula, developed from the test results on relatively high carbon steels, was used quite extensively. By the early seventies, it was realized that for lower carbon steels (.07 to .16 wt %), the IIW carbon equivalent formula did not satisfactorily assess weldability, and the P_{cm} equivalent was developed by Ito and Bessyo⁽⁴⁾ for such steels. More recently, Yurioka⁽²⁴⁾ combined the two formulae to get CEN, which is apparently valid for both the relatively low and high carbon steels.

These three carbon equivalents for the steels investigated are given in Table 9, along with the weldability ratings as assessed by the different tests. The results confirm that the conventional IIW carbon equivalent is not suitable for assessing the weldability of the relatively low carbon microalloyed steels such as those investigated here.

The other two carbon equivalents viz P_{cm} and CEN rank the steels in the same order, and the weldability test results substantially agree with that. However, it is difficult to say if one of these should be preferred over the other. Empirical relations are

available which can be used to predict preheat temperature to avoid cracking, in say the Tekken test, as a function of weld metal hydrogen content, restraint and either of the two carbon equivalents. However, both the carbon equivalents would predict preheats higher than observed, and in about the same range. For example, using CEN, the preheats for no cracking are estimated to be 30°, 50° and 100°C for A710, Lloyds LT 60 and BS 4360 steels respectively,⁽²⁵⁾ whereas in fact they were found to be <20°, <20° and 20 to 50°C respectively.

5. SUMMARY

Tests for cold cracking susceptibility have been carried out to assess the weldability of steels A710 Gr. A, Cl. 3 and Lloyds LT 60, and BS 4360 Gr. 50 E.

5.1 Hardening Curves

1. As carbon equivalent (CEN or P_{cm}) decreases, there is a wider range of acceptable welding parameters as indicated by:
 - a) lower maximum hardness in the HAZ.
 - b) lower slope on the hardening curves in the as-welded condition.
 - c) higher critical cooling rates at selected hardness levels (usually 300-350 HV₁₀).
2. Carbon content governs the maximum hardness which can be reached.
3. Postweld stress relief heat treatment leads to a decrease in HAZ hardness. The effect is less for steel A710 Gr. A, Cl. 3 than for the other steels, possibly due to solid solution alloying elements and precipitation hardening effects.
4. A710 Gr. A, Cl. 3 shows the lowest HAZ hardness, and hence the most promise for good weldability.

5.2 Tekken Tests

1. Gap size may control the type of cracking (HAZ or WM) which occurs in the Tekken test.
2. Steel A710 Gr. A, Cl. 3 showed no HAZ cracking even in the controlled gap test pieces.
3. Preheat requirements in welding A710 steel may be governed by the cold cracking susceptibility of the weld metal used.
4. The critical preheat for Lloyds LT 60 steel is less than room temperature.
5. The critical preheat for BS 4360 Gr. 50E steel in the Tekken test is between 25 and 50°C.

5.3 CTS Tests

1. The critical preheat for steel A710 Gr. A, Cl. 3 is less than -30°C.
2. Lloyds LT 60 and BS 4360 Gr. 50E steels both show a critical preheat level between -30 and 25°C.

5.4 Implant Tests

1. The weldability of the three steels as indicated by the lower critical stress is not entirely consistent with the results of the other three tests.
2. Normalizing the lower critical stress values with respect to the apparent tensile strength of the HAZ (based on hardness) brought the results in line with the other tests viz. A710

having the best weldability, and the other two having lower but about the same resistance to cold cracking.

6. CONCLUSIONS

1. After performing four different weldability tests, the three steels tested are rated in terms of decreasing weldability as follows:
 - i) A710 Gr. A, Cl. 3
 - ii) Lloyds LT 60
 - iii) BS 4360 Gr. 50 E
2. In the case of A710 Gr. A Cl. 3 steel, the preheat requirements are likely to be governed by the weld metal susceptibility to cold cracking, even with E7018 type of weld metal, on account of the dilution effects from the alloying elements in the base material.
3. Welding of steels such as Lloyds LT 60 at low ambient temperature (-30°C or below) could increase the risk of cold cracking in HAZ, and thus needs to be explored further.
4. The IIW carbon equivalent formula does not adequately assess the relative weldability of the three steels.

The P_{cm} and CEN carbon equivalent formula rank the steels in the same order as the weldability tests; however, the preheats predicted for no cracking in the Tekken tests, based on empirical relationships developed, are higher than those observed in the tests.

ACKNOWLEDGEMENTS

The author would like to thank D. Skinner, G. Williams, and F. Rauche for their help with the experimental work. The assistance of P. Last and H. Barton in preparing this report is also appreciated. Special thanks go to M. Letts and CANMET/PMRL for assistance and use of equipment for implant testing.

REFERENCES

1. Graville, B.A. "The Principles of Cold Cracking Control in Welds". Dominion Bridge Company, Ltd., 1975.
2. Pedder, C. "CTS Testing Procedures: The Present Position". The Welding Institute, Res. Bull., Sept. 1975, pp. 264-266.
3. Suzuki, H. "Cold Cracking and its Prevention in Steel Welding". (Rep. 1) IIW DOC IX-1074-78 (1978), 1-10. Trans. JWS, 9(1978), No. 2, pp. 140-149.
4. Ito, Y., and Bessyo, K. "Cracking Parameter of High Strength Steels Related to HAZ Cracking". Rep. 1, Jul. JWS 37(1968), No. 9, 983-991, Rep. 2, ibid. 38(1969), No. 10 1134-1144 (Japanese).
5. Campbell, W.P. "Experiences with HAZ Cold Cracking Tests on a C-Mn Structural Steel". Welding Research Supplement, May 1976, p. 135s.
6. Masubuchi, K. "Analysis of Welded Structures, Residual Stresses, Distortion, and Their Consequences". International Series on Materials Science and Technology, Vol. 33, 1980, p. 556.
7. Japanese Industrial Standard. "Method of Y-Groove Cracking Test". JIS Z 3158 - 1966.
8. Gordine, J. "The Weldability of Some Arctic Canada Line Pipe Steels". Welding Journal Research Supplement, July 1977.
9. Bernard, G. "A Viewpoint on the Weldability of C-Mn and Microalloyed Structural Steels". "Microalloying 75" pp. 52-66, Session 3, Washington, D.C. 1975.
10. Linnert, G.E. "Welding Metallurgy, Carbon and Alloy Steels". 3rd Ed., Vol. 2, pp. 331-334, AWS, New York, 1967.
11. Abson, D.J. and Dolby, R.E. "A Scheme for the Quantitative Description of Ferritic Weld Metal Microstructures". The Welding Institute, Res. Bull., April 1980, pp. 100-103.
12. Reed-Hill, R.E. "Physical Metallurgy Principles". D. Van Nostrand Co. Inc., 1964, pp. 506-511.
13. Hart, P.H.M. Personal Correspondence.
14. Suzuki, H. "Cold Cracking and its Prevention in Steel Welding". Transactions of the Japan Welding Society, Vol. 10, No. 2 (1979).

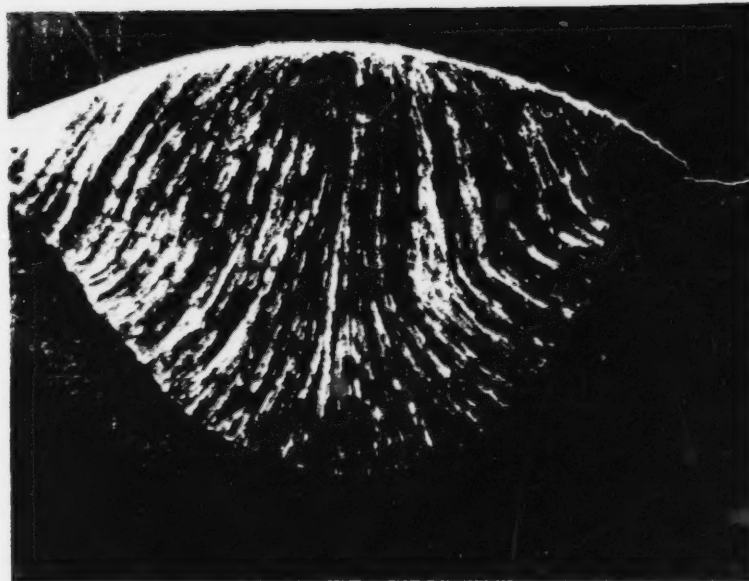


Figure 1: Location of HAZ Hardness Reading in
(a) Concave Coarse Grained Region, and
(b) Coarse Grain Region at the Bottom of the Weld
(Neg. 6670; Mag. X 12; Etch - Vilella's Reagent)

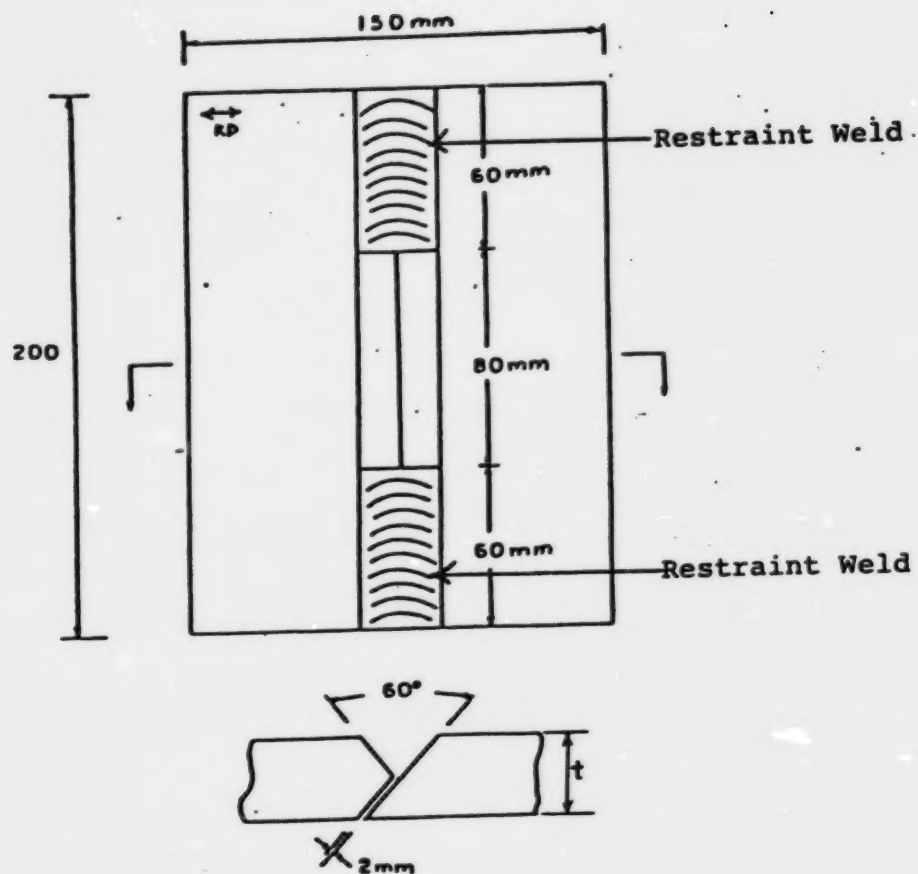


Figure 2: Tekken Test Block Dimensions

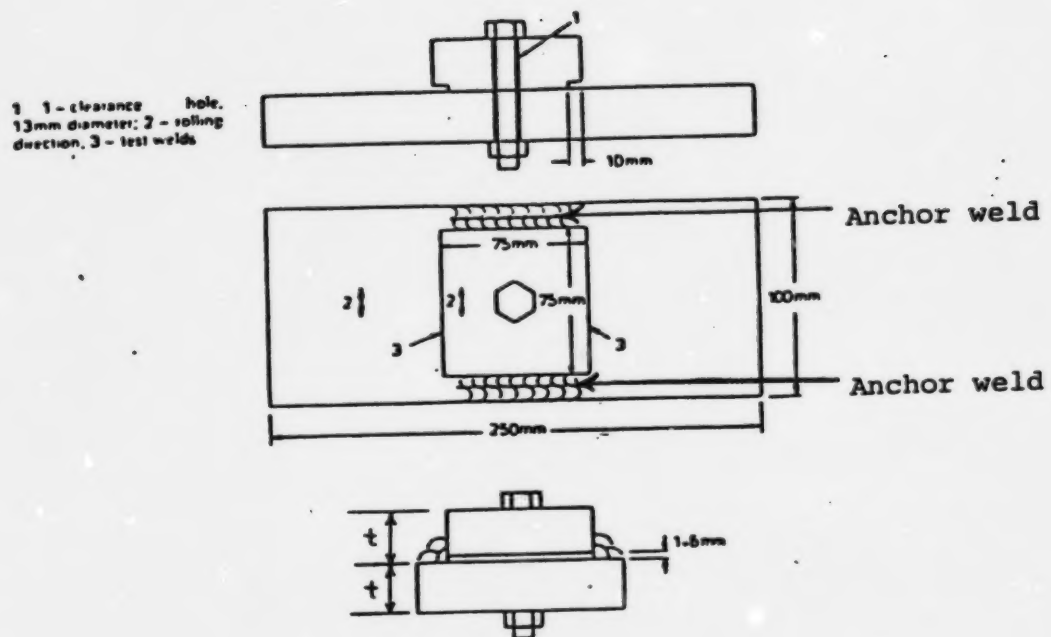
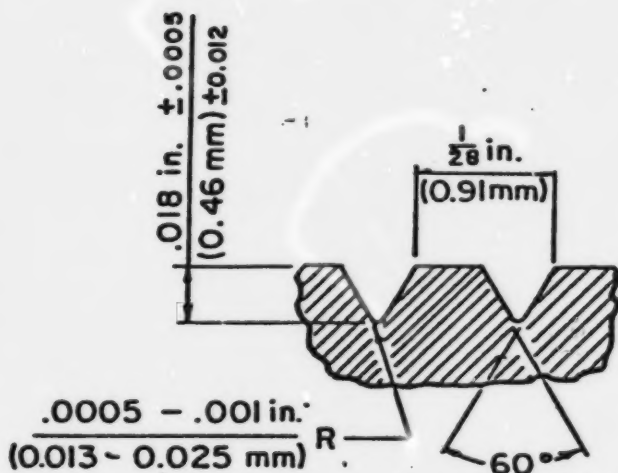
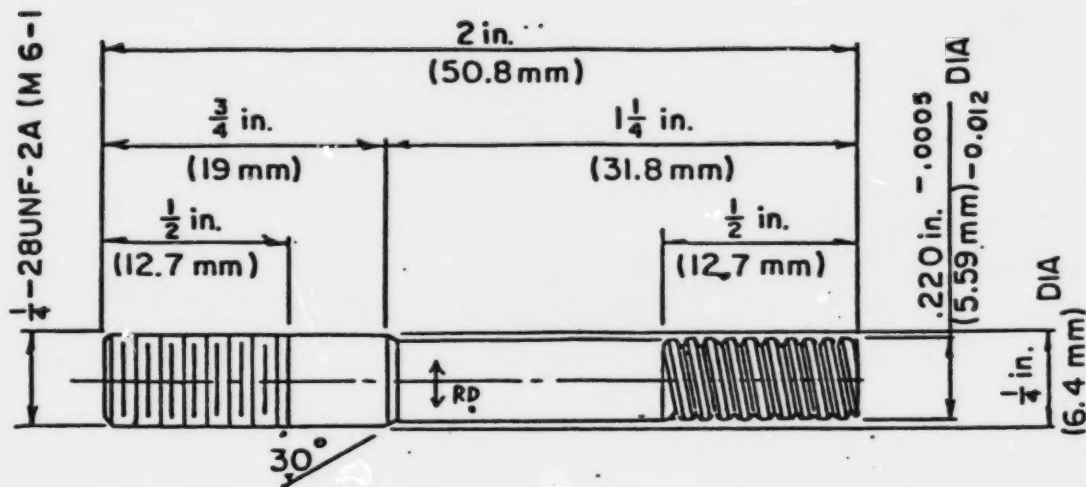


Figure 3: Controlled Thermal Severity Test Block Dimensions



ENLARGED HELICAL NOTCH DETAIL

THIS DRAWING TO BE USED IN CONJUNCTION WITH SCALE: DOUBLE SIZE
DRAWING NO. 147

IMPLANT SPECIMEN

REMARKS:

- 1) MATERIAL TO BE STATED ON WORK ORDER.
- 2) OPEN DIMENSIONS TOLERANCE ±.010 in. (0.25 mm)
- 3) GENERAL FINISH 63 MICRO - INCHES (1.6 μm)

P.M.D. 568 BOOTH ST.
OTTAWA

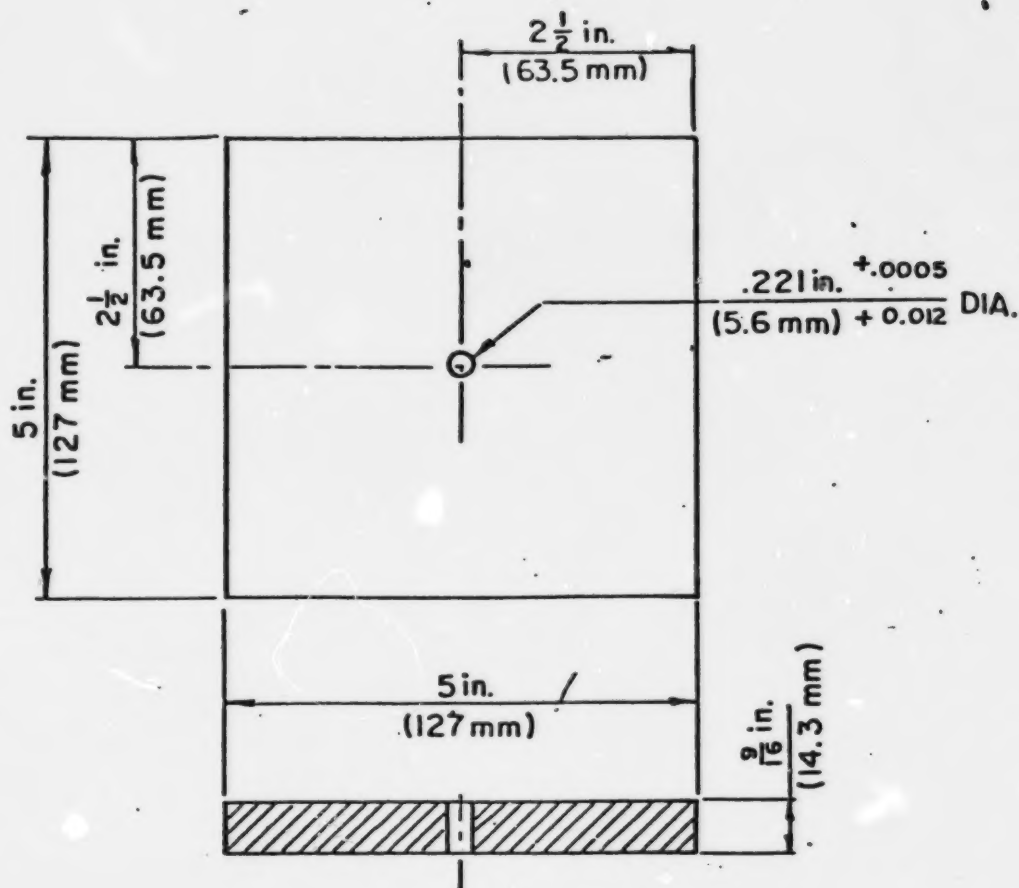
DRAWN BY: H. LETTING

FOR: J. GORDINE

DATE: 9 JUNE, 75

DRAWING NO. 146

Figure 4a: Implant Specimen Dimensions



THIS DRAWING TO BE USED IN CONJUNCTION WITH
DRAWING NO. 146

SCALE: HALF SIZE

SPECIMEN PLATE FOR IMPLANT SPECIMEN

REMARKS:

- 1) MATERIAL TO BE STATED ON WORK ORDER.
- 2) OPEN DIMENSIONS TOLERANCE $\pm .010$ in. (0.25 mm)
- 3) GENERAL FINISH 63 MICRO-INCHES (1.6 μ m)

P.M.D. 568 BOOTH ST.
OTTAWA

DRAWN BY: H.LETTING

FOR: J.GORDINE

DATE: 9 JUNE, 75

DRAWING NO. 147

Figure 4b: Backing Plate Dimensions

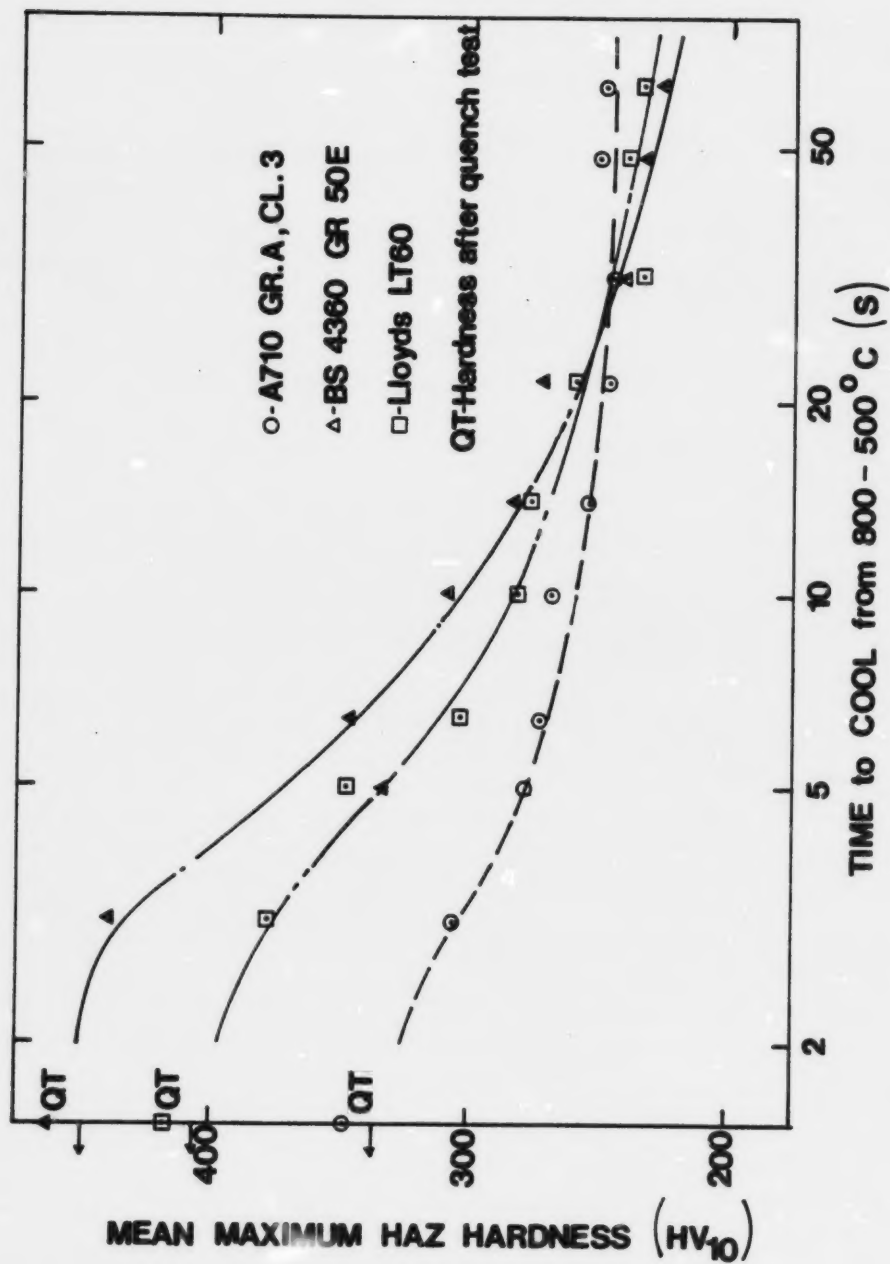


Figure 5: Hardening Curves for the Three Steels in the As-welded Condition.

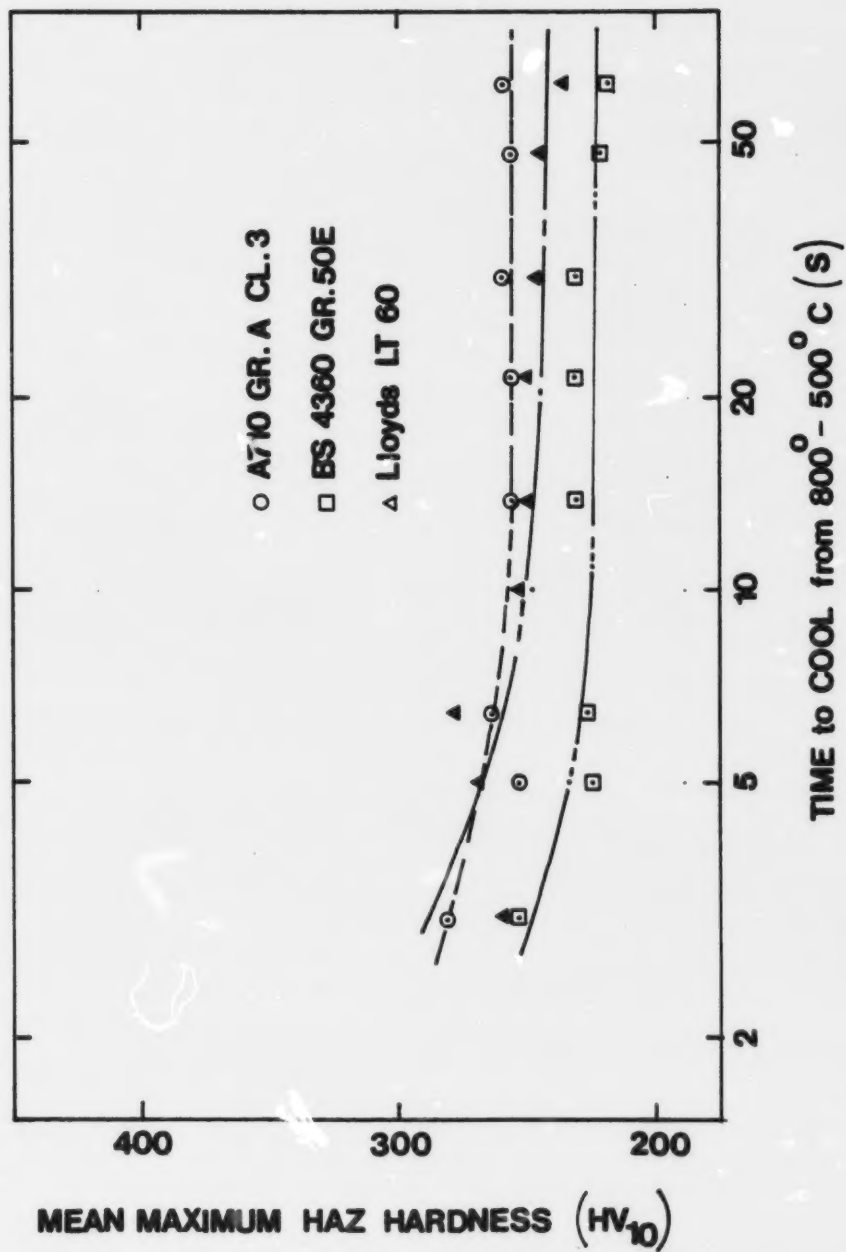
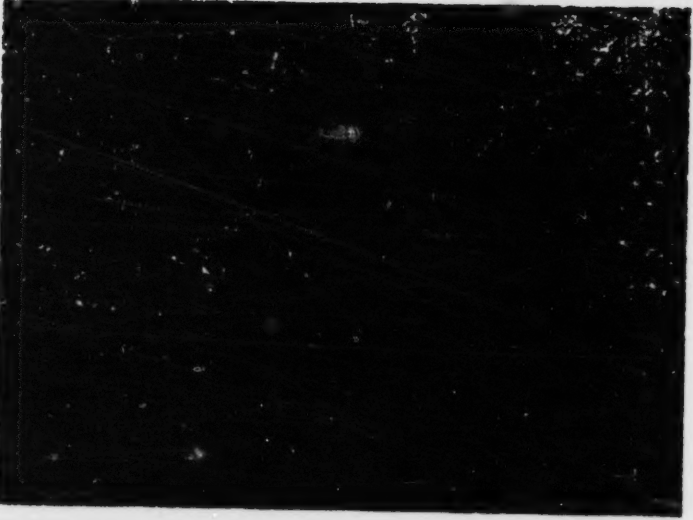


Figure 6: Hardening Curves for the Three Steels in the Stress-relieved Condition.

- 
- (a) A710 Gr A, C1 3
As Received
(Neg. 7404; Mag. X 200;
Etch - 4% picral with
2% nital)

- 
- (b) Heat Input 0.5 KJ/mm
Grain Size 8
(Neg. 7393; Mag. X 200;
Etch - 4% picral with
2% nital)

- 
- (c) Heat Input 0.8 KJ/mm
Grain Size 7
(Neg. 7394; Mag. X 200;
Etch - 4% picral with
2% nital)

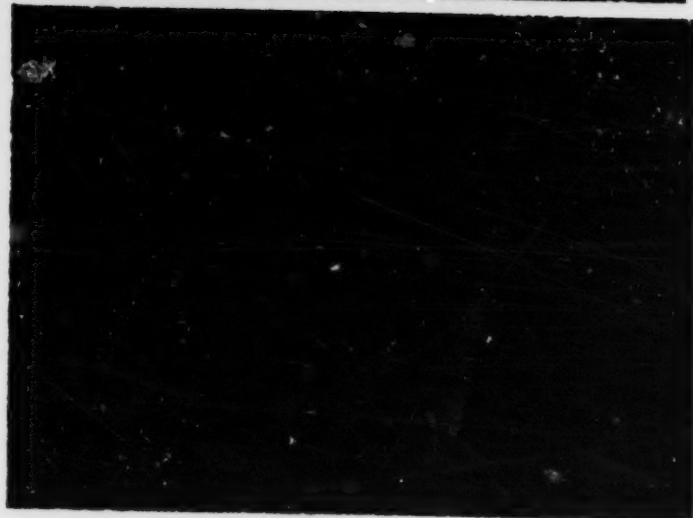
Figure 7: HAZ Microstructure of Steel A710 Gr A, C1 3 in the As-welded Condition



(d) Heat Input 1.1 KJ/mm
Grain Size 6
(Neg. 7395; Mag. X 200;
Etch - 4% picral with
2% nital)



(e) Heat Input 1.7 KJ/mm
Grain Size 4
(Neg. 7396; Mag. X 200;
Etch - 4% picral with
2% nital)



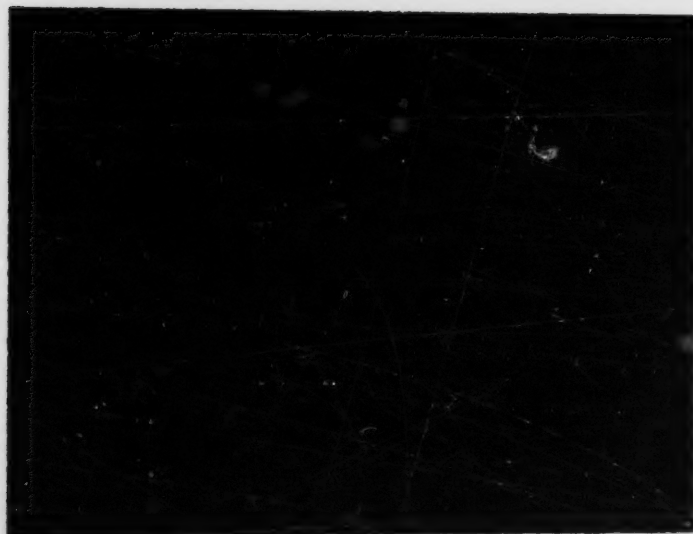
(f) Heat Input 2.3 KJ/mm
Grain Size 3
(Neg. 7397; Mag. X 200;
Etch - 4% picral with
2% nital)



(g) Heat Input 3.5 KJ/mm
Grain Size 3
(Neg. 7398; Mag. X 200;
Etch - 4% picral with
2% nital)



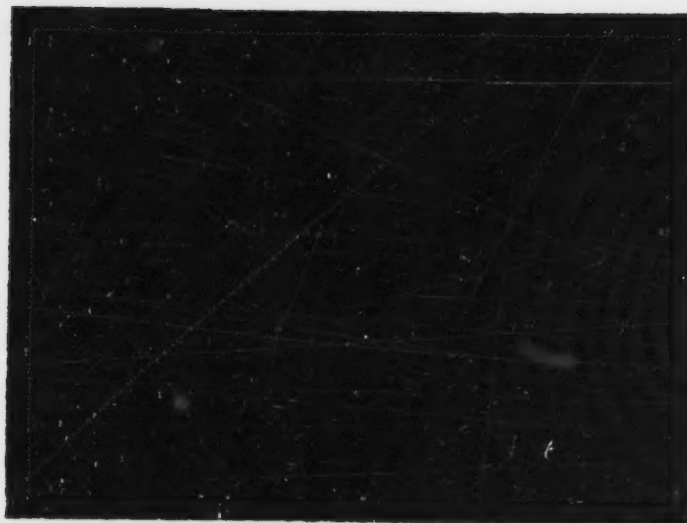
(h) Heat Input 5.1 KJ/mm
Grain Size 2
(Neg. 7399; Mag. X 200;
Etch - 4% picral with
2% nital)



(i) Heat Input 8.0 KJ/mm
Grain Size 2
(Neg. 7401; Mag. X 200;
Etch - 4% picral with
2% nital)



(j) Heat Input 10.0 KJ/mm
Grain Size 1
(Neg. 7400; Mag. X 200;
Etch - 4% picral with
2% nital)



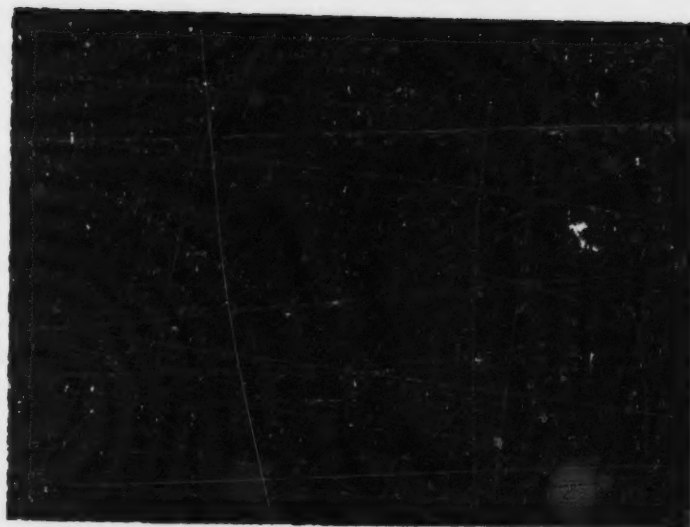
(a)



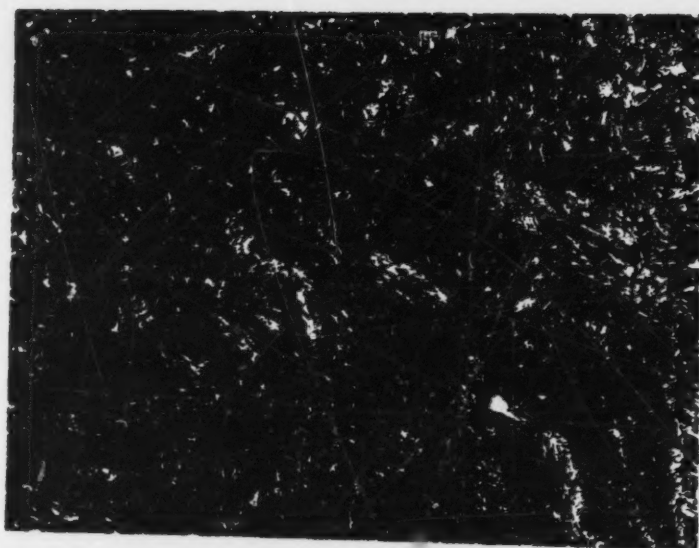
(b)

Figure 8: HAZ microstructure of Steel A710 Gr A, C1 3 in the Stress-Relieved Condition at Heat Inputs of (a) 0.5 KJ/mm and (b) 10.0 KJ/mm

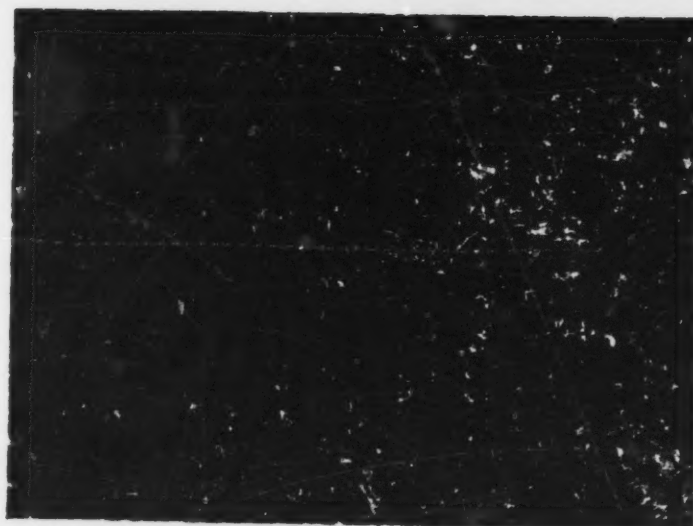
(Neg. 7530, 7529; Mag. X 200; Etch - 4% picral with 2% nital)



(a) Lloyds LT 60 -
As received
(Neg. 7262; Mag. X200;
Etch - 4% picral with
2% nital)

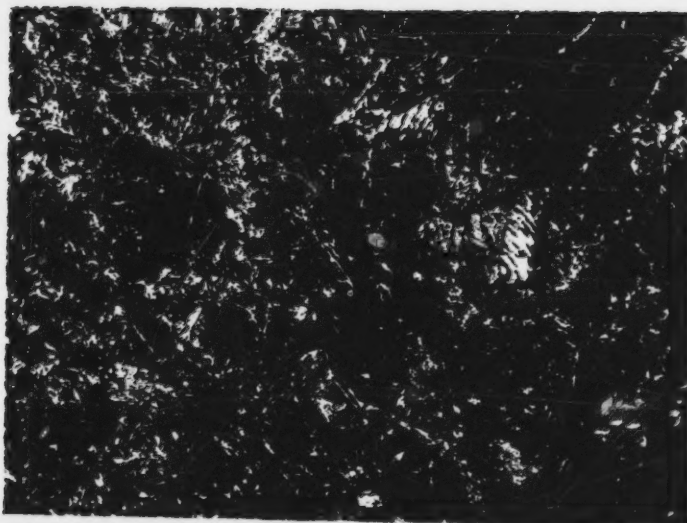


(b) Heat Input 0.5 KJ/mm
Grain Size 6
(Neg. 7263; Mag. X 200;
Etch - 4% picral with
2% nital)

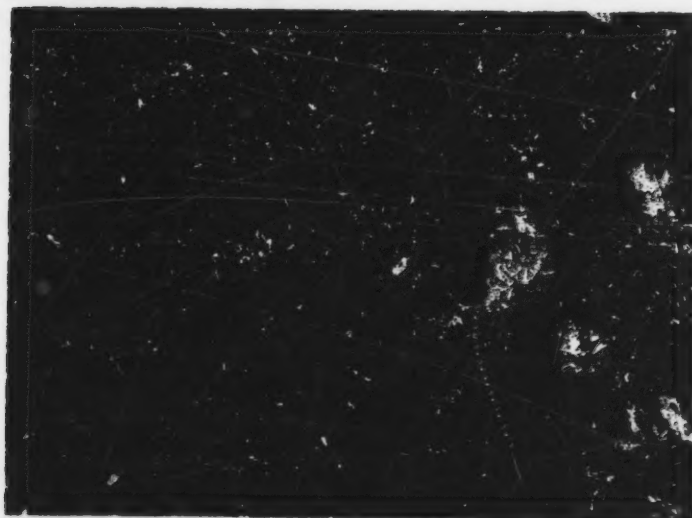


(c) Heat Input 0.8 KJ/mm
Grain Size 6
(Neg. 7264; Mag. X 200;
Etch - 4% picral with
2% nital)

Figure 9: HAZ Microstructure of Lloyds LT 60 Steel in the As-welded Condition



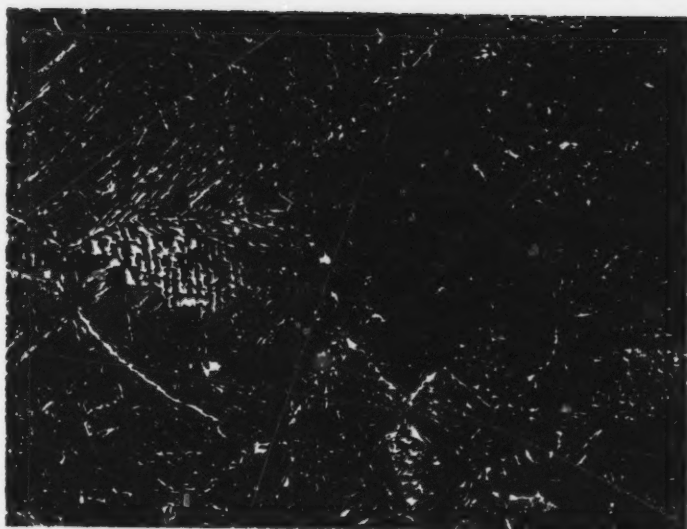
(d) Heat Input 1.1 KJ/mm
Grain Size 5
(Neg. 7265; Mag. X 200;
Etch - 4% picral with
2% nital)



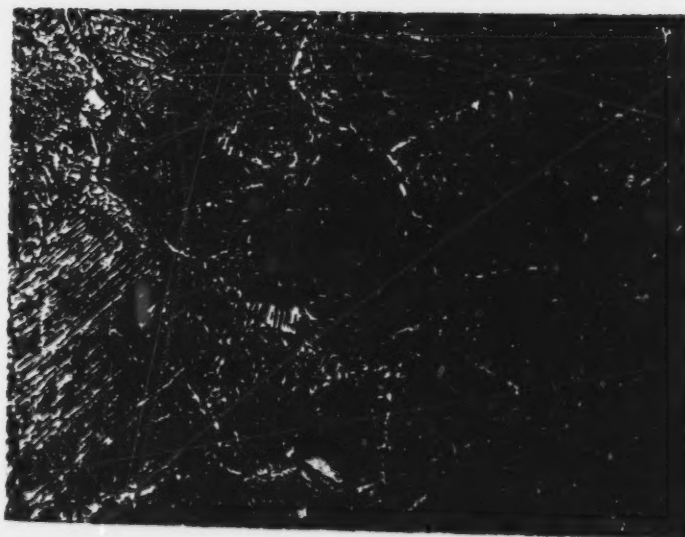
(e) Heat Input 1.7 KJ/mm
Grain Size 5
(Neg. 7266; Mag. X 200;
Etch - 4% picral with
2% nital)



(f) Heat Input 2.3 KJ/mm
Grain Size 4
(Neg. 7267; Mag. X 200;
Etch - 4% picral with
2% nital)



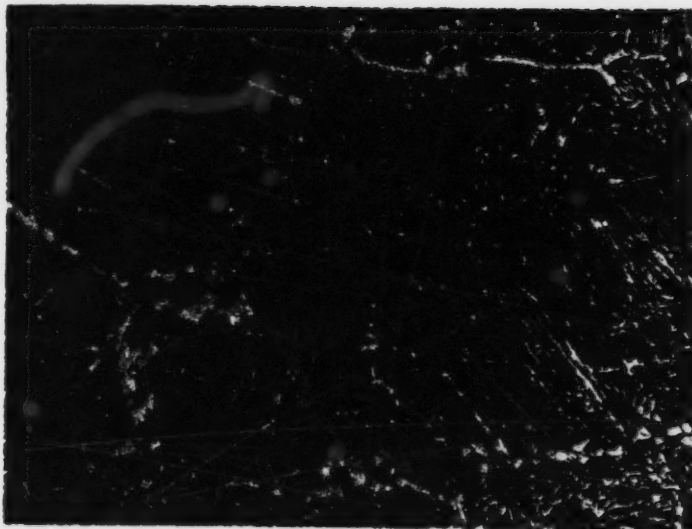
(g) Heat Input 3.5 KJ/mm
Grain Size 3
(Neg. 7268; Mag. X 200;
Etch - 4% picral with
2% nital)



(h) Heat Input 5.1 KJ/mm
Grain Size 2
(Neg. 7269; Mag. X 200;
Etch - 4% picral with
2% nital)



(i) Heat Input 8.0 KJ/mm
Grain Size 1
(Neg. 7270; Mag. X 200;
Etch - 4% picral with
2% nital)



(j) Heat Input 10.0 KJ/mm
Grain Size 1
(Neg. 7286; Mag. X 200;
Etch - 4% picral with
2% nital)



(a)



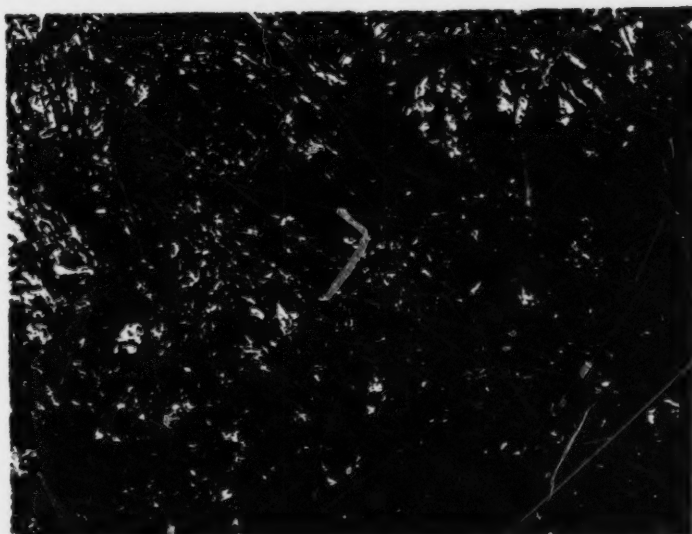
(b)

Figure 10: HAZ microstructure of Lloyds LT 60 Steel in the Stress Relieved Condition at Heat Inputs (a) 0.5 KJ/mm and (b) 10.0 KJ/mm

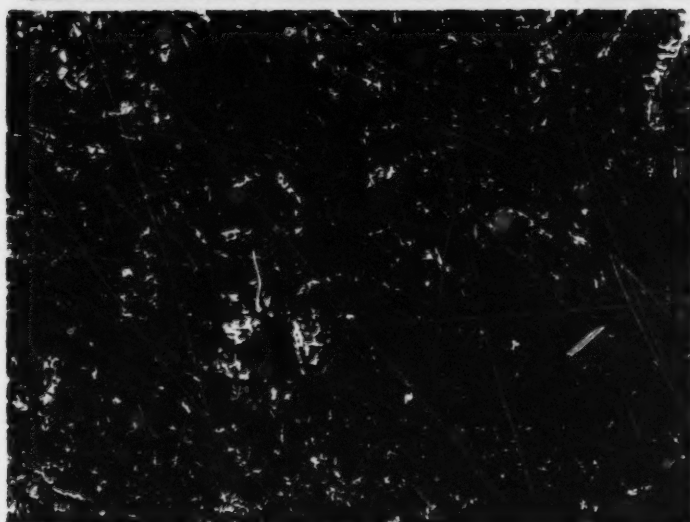
(Neg. 7527, 7528; Mag. X 200; Etch - 4% picral with 2% nital)



- (a) BS 4360 Gr 50E -
As Received
(Neg. 7288; Mag. X 200;
Etch - 4% picral with
2% nital)



- (b) Heat Input 0.5 KJ/mm
Grain Size 6
(Neg. 7287; Mag. X 200;
Etch - 4% picral with
2% nital)

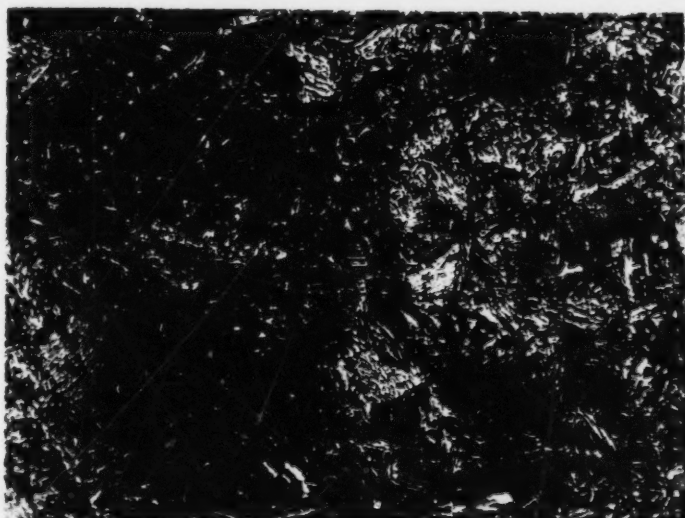


- (c) Heat Input 0.8 KJ/mm
Grain Size 6
(Neg. 7289; Mag. X 200;
Etch - 4% picral with
2% nital)

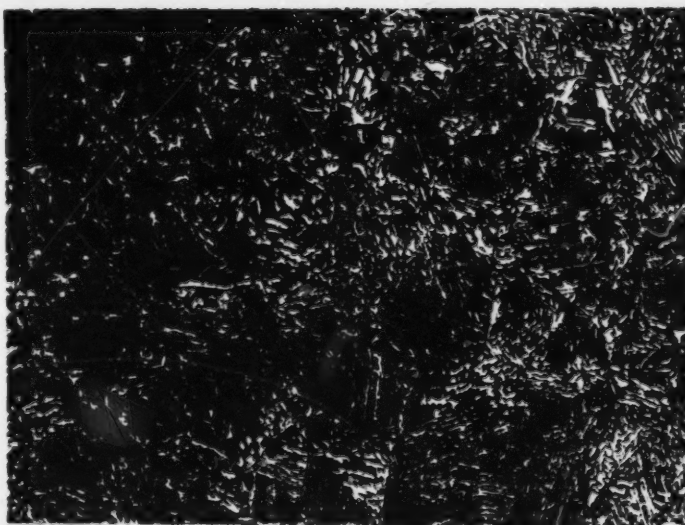
Figure 11: HAZ Microstructure of Steel BS 4360 Gr 50E in the
As Welded Condition



(d) Heat Input 1.1 KJ/mm
Grain Size 6
(Neg. 7290; Mag. X 200;
Etch - 4% picral with
2% nital)



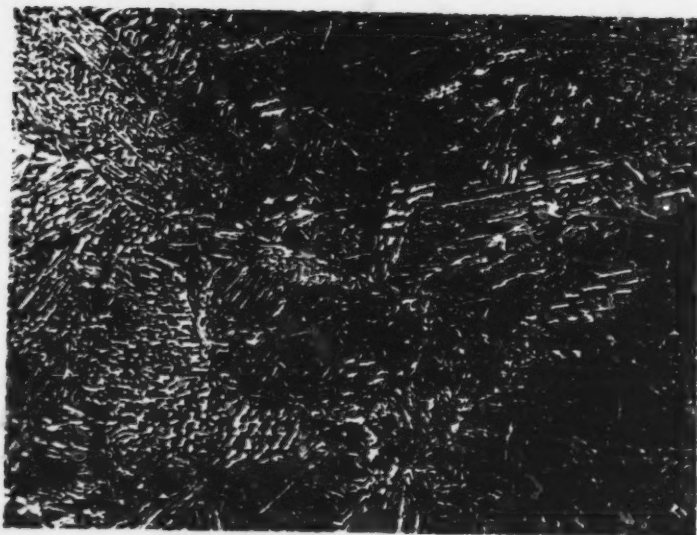
(e) Heat Input 1.7 KJ/mm
Grain Size 5
(Neg. 7291; Mag. X 200;
Etch - 4% picral with
2% nital)



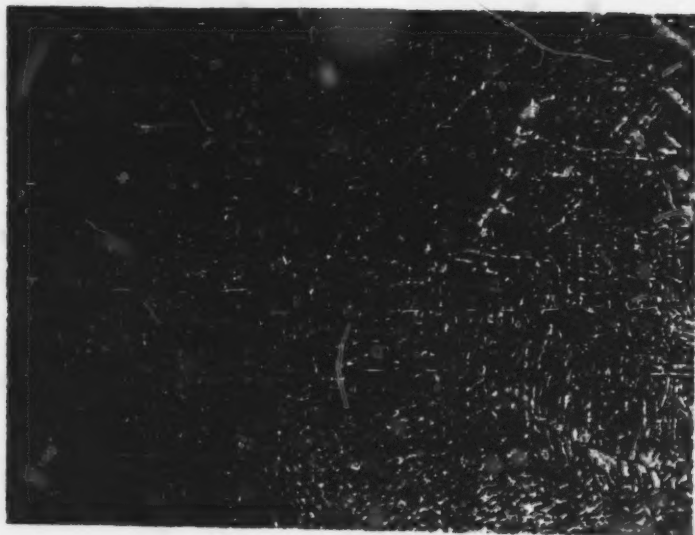
(f) Heat Input 2.3 KJ/mm
Grain Size 4
(Neg. 7292; Mag. X 200;
Etch - 4% picral with
2% nital)



(g) Heat Input 3.5 KJ/mm
Grain Size 2
(Neg. 7293; Mag. X 200;
Etch - 4% picral with
2% nital)



(h) Heat Input 5.1 KJ/mm
Grain Size 2
(Neg. 7294; Mag. X 200;
Etch - 4% picral with
25 nital)



(i) Heat Input 8.0 KJ/mm
Grain Size 1
(Neg. 7295; Mag. X 200;
Etch - 4% picral with
2% nital)



(j) Heat Input 10.0 KJ/mm
Grain Size 1
(Neg. 7296; Mag. X 200;
Etch - 4% picral with
2% nital)



(a)



(b)

Figure 12: HAZ microstructure of Steel BS 4360 Gr 50E in the Stress Relieved Condition at Heat Inputs (a) 0.5 KJ/mm and (b) 8.0 KJ/mm

(Neg. 7526, 7524; Mag. X 200; etch - 4% picral with 2% nital)



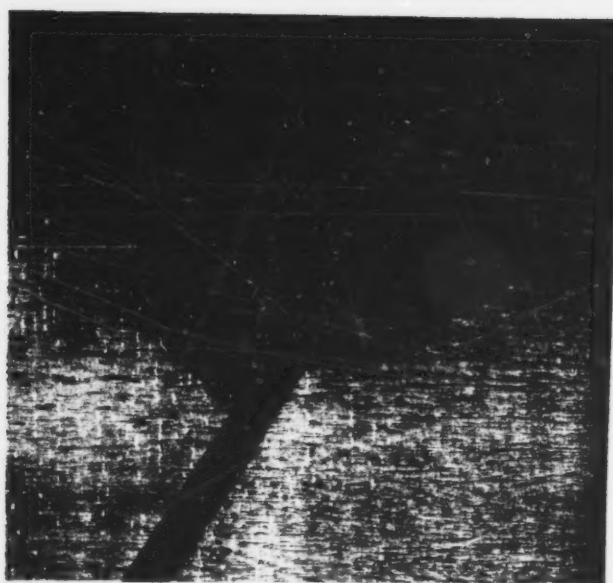
Figure 13: The effect of root gap in Steel BS 4360 Gr 50E on the type of cracking occurring, all other conditions held constant
(Neg. 7513; Mag. X 2; Etch - 10% nital)



(a)



(b)



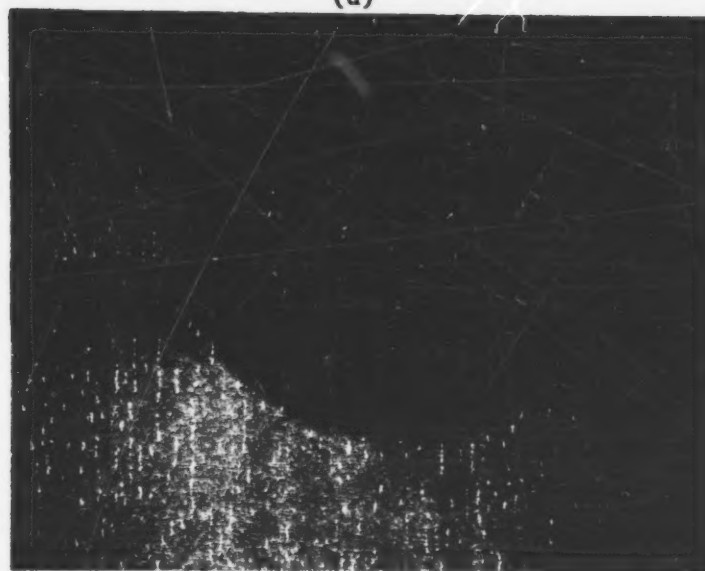
(c)

Figure 14: Typical weld metal and HAZ cracks in
(a) Steel A710 Gr A C1 3 with gap size controlled
(b) Steel BS 4360 Gr 50E with gap size controlled, and
(c) Steel BS 4360 Gr 50E with reduced gap

(Neg. 7534, 7533, 7535; Mag. X 5; etch -2% nital)



(a)



(b)

Figure 15: Typical weld metal (a) and HAZ (b) cracks found in the CTS test

(Neg. 7536, 7537; Mag. X 5; Etch -2% nital)

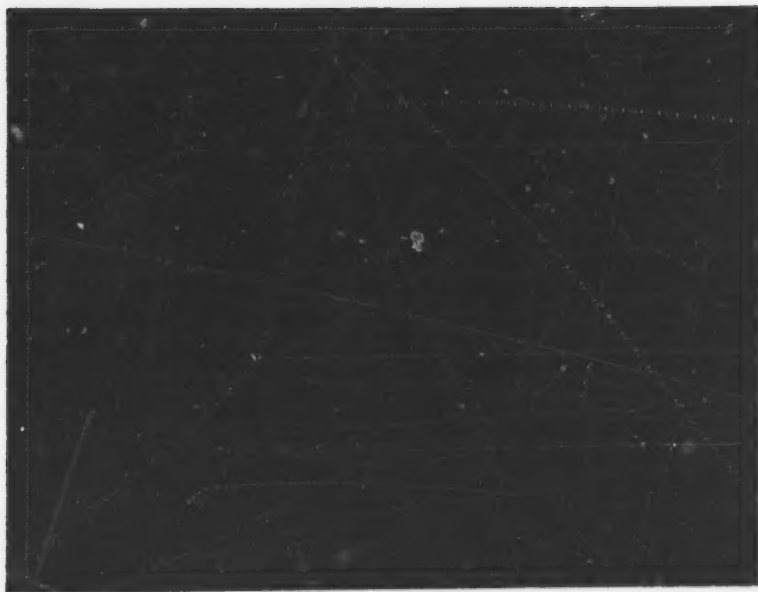


Figure 16: HAZ cracks in steel BS 4360 Gr 50E welded at -30°C
(Neg. 7452; Mag. X 12; Etch -2% nital)

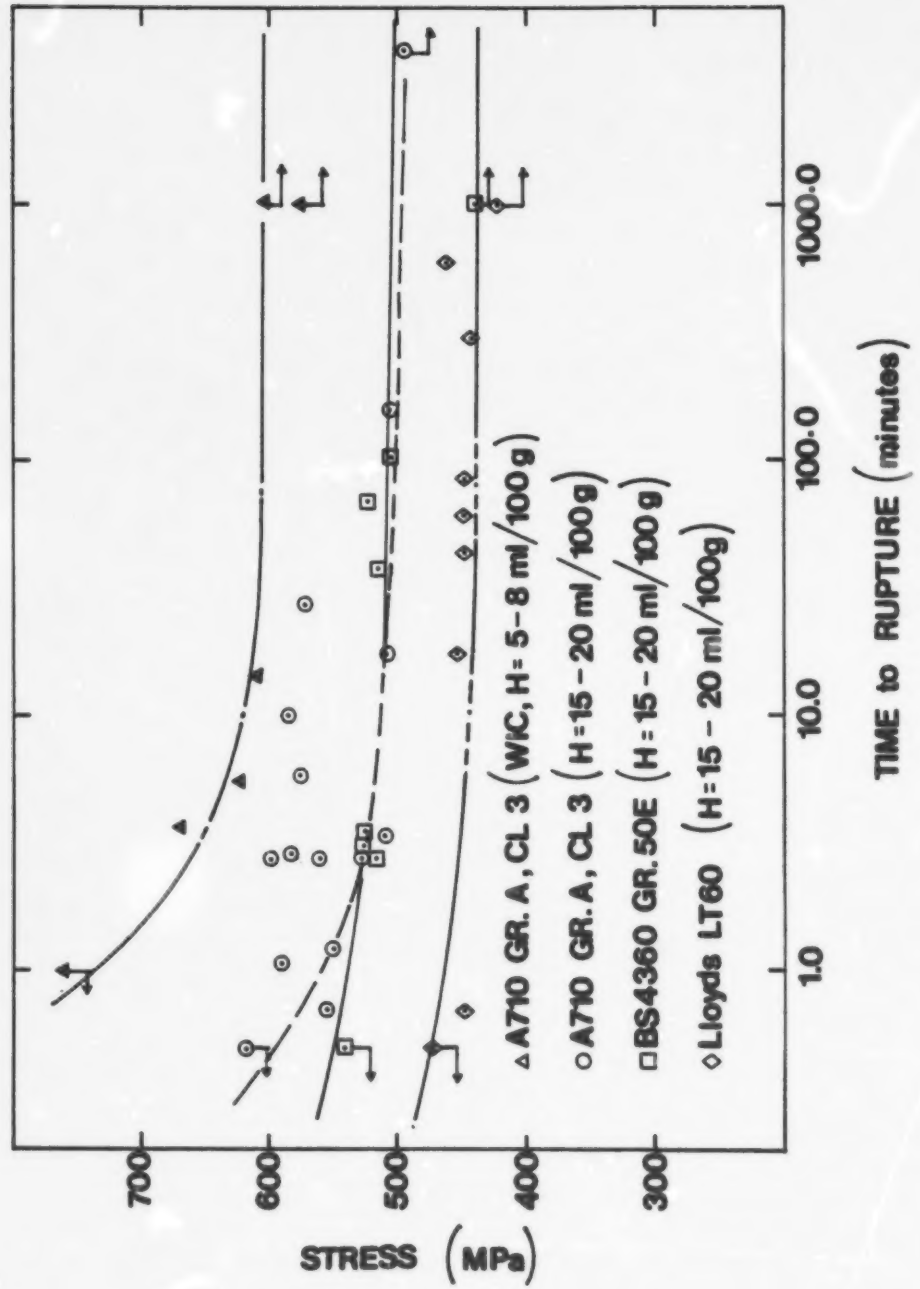


Figure 17: Implant Test Results - Applied Stress vs. Time to Rupture.



Figure 18: Typical HAZ cracks found in ruptured implant specimens

(Neg. 7275; Mag. X 7; Etch -2% nital)

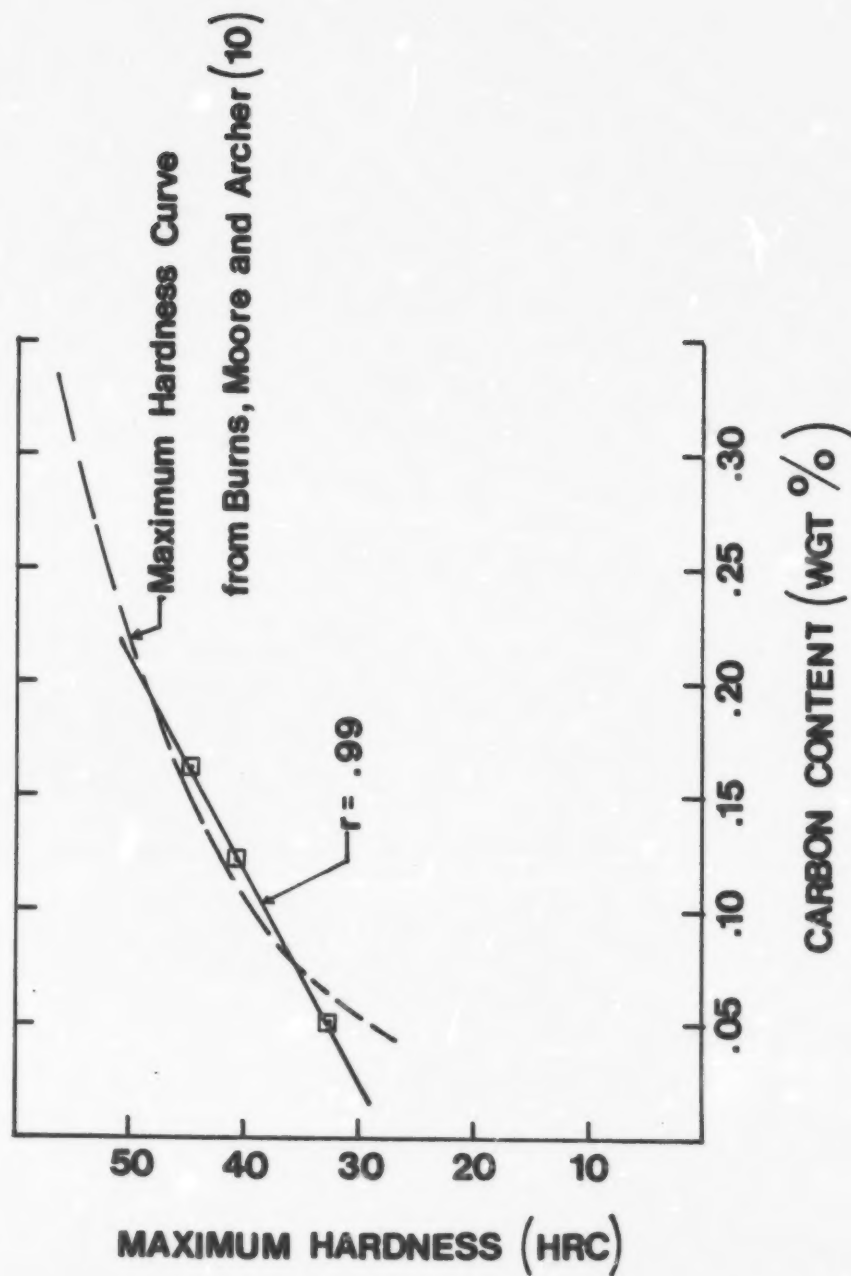
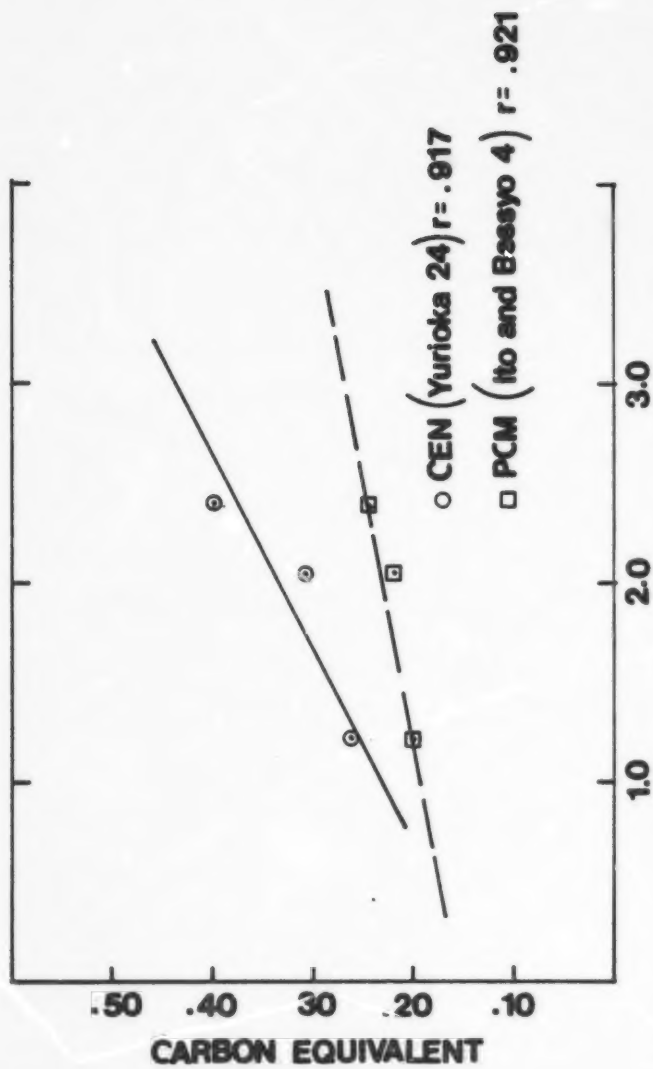


Figure 19: Relationship between Maximum HAZ Hardness and Carbon Content.



CRITICAL COOLING TIME for HAZ HARDNESS of 300 HV₁₀ [LOG of TIME (S)]

Figure 20: Logarithmic Relationship between Carbon Equivalent and Cooling Time from 800 to 500°C to achieve a HAZ Hardness of 300 HV₁₀.

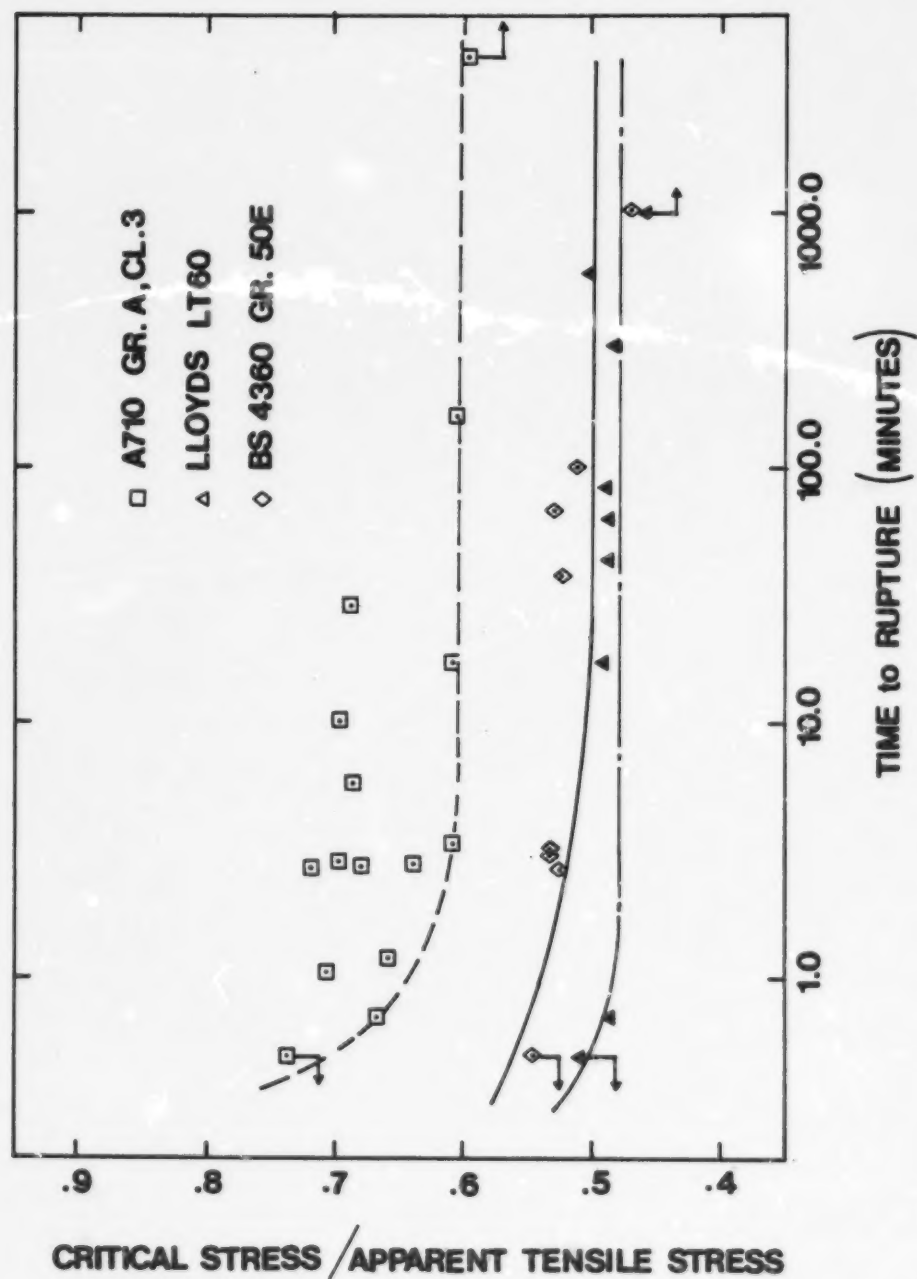


Figure 21: The Ratio of Applied Stress to Tensile Stress Estimated from HAZ Hardness vs. the Time to Rupture.

TABLE 1: Chemical Compositions of the Three Experimental Steels (in wt %)

Element Steel	C	Mn	Si	Cr	Mo	V	Ni	Cu	P	S	Nb	Al	N	CE(IIW)	*	** P _{cm}	*** CEN
A710 Gr A Cl 3	.05	.42	.23	.73	.21	.002	1.03	1.06	.01	.009	.042	.023	.010	.448		.200	.260
Lloyds LT 60	.12	1.29	.26	.15	.05	.10	.15	.006	.01	.006	.01	.03	.006	.398		.217	.308
BS 4360 Gr 50 E	.16	1.42	.30	.02	<.01	<.01	.03	.07	.012	.011	.02	.03	.006	.411		.247	.396

* $CE(IIW) = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$

** $P_{cm} = C + (Mn + Cu + Cr)/20 + Si/30 + Ni/60 + Mo/15 + V/10 + 58$

*** $CEN = C + A(C)[Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr + Mo + V + Nb)/5 + 58]$

$A(C) = .75 + .25 \tanh [20(C - 0.12)]$

TABLE 2: Mechanical Properties of the Three Experimental Steels

Properties Steel	YS (MPa)	TS (MPa)	Elongation (% in. 2 in.)	Notch Toughness (CVNL)
A710 Gr A Cl 3	516	595	25	192 J @ -64°C
Lloyds LT 60	386	516	30	211 J @ -60°C
BS 4360 Gr 50 E	367	518	28	112 J @ -50°C

TABLE 3: Welding Parameters for Bead on Plate Welds

Bead	Heat Input (kJ/mm)	Wire Dia. (mm)	Current (Amps)	Voltage (Volts)	Travel Speed (mm/s)	Cooling Times 800-500°C (s)
1	0.5	0.84	150	26	7.6	3.1
2	0.8	1.8	250	25	7.6	5.0
3	1.1	1.8	300	27	7.6	6.4
4	1.7	3.8	500	26	7.6	10.0
5	2.3	3.8	550	30	7.1	13.8
6	3.5	3.8	600	30	5.0	21.5
7	5.1	3.8	700	34	4.6	31.0
8	8.0	3.8	700	34	3.0	48.5
9	10.0	3.8	750	34	2.5	62.0

TABLE 4: Conditions for Tekken Tests

<u>Steel Type</u>	<u>Electrode</u>	<u>Preheat Temp. (°C)</u>	<u>Hydrogen Level</u>
A710 Gr A, C1 3 (controlled gap)	E6010	25 (Rm Temp)	*low
	E11018	25	low
	E7018	-30	**high
	E7018	25	high
	E8018-C1	25	low,high
	E8018-C1	50	low,high
	E8018-C1	100	low,high
Lloyds LT 60 (controlled gap)	E8018-C1	150	low,high
	E7018	-30	high
	E7018	25	high
	E8018-C1	25	low,high
	E8018-C1	50	low,high
	E8018-C1	100	low,high
BS 4360 Gr 50 E (controlled gap) (controlled gap)	E8018-C1	150	low,high
	E7018	-30	high
	E7018	25	high
	E7018	50	high
	E7016	25	high
	E7016	50	high
	E7016	100	high
	E8018-C1	25	low
	E8018-C1	50	low
	E8018-C1	100	low
	E8018-C1	150	low

*low hydrogen levels considered to be 2 → 10 ml/100g deposited hydrogen.

**high hydrogen levels considered to be over 10 ml/100g.

TABLE 5: Conditions for CTS Tests

<u>Steel Type</u>	<u>Electrode</u>	<u>Preheat Temp. (°C)</u>	<u>Hydrogen Level</u>
A710 Gr A, C1 3 and Lloyds LT 60	E7018	-30	*low,**high
	E8018-C1	25	low,high
	E8018-C1	50	low,high
	E8018-C1	100	low,high
	E8018-C1	150	low,high
BS 4360 Gr 50 E	E7018	-30	low,high
	E7016	25	high
	E7016	50	high
	E7016	100	high
	E7016	150	high
	E8018-C1	25	low
	E8018-C1	50	low
	E8018-C1	100	low
	E8018-C1	150	low

*low hydrogen levels considered to be 2 → 10 ml/100g deposited hydrogen.

**high hydrogen levels considered to be over 10 ml/100g.

TABLE 6: Parameters for Implant Tests

Process:	Shielded metal arc welding (SMAW)
Electrode:	E8018-C1, 4 mm
Current:	193 Amps DC +ve
Voltage:	22 Volts
Travel Speed:	2.5 mm/s
Heat Input:	1.7 kJ/mm
Hydrogen Level:	Electrodes exposed 16-24 hours at 90% humidity to achieve levels of 15-20 ml/100g
Preheat:	None

TABLE 7: Summary of Tekken Test Results

<u>Steel Type</u>	<u>Electrode</u>	<u>Preheat (°C)</u>	<u>Approximate Hydrogen (ml/100g)</u>	<u>Cracking: Type, No. of Cracked Sections</u>	<u>Notes</u>
A710 Gr A, C1 3	E7018	-30	15	WM, 6/6	Controlled gap
	E7018	25	14	WM, 6/6	
	E8018-C1	25	3	WM, 5/5	
	E8018-C1	50	3	WM, 3/4	
	E8018-C1	100	3	None	
	E8018-C1	100	8	WM, 5/5	
Lloyds LT 60	E8018-C1	150	9	None	Controlled gap
	E7018	-30	15	WM, 5/6	
	E7018	25	10	None	
	E8018-C1	25	5	None	
	E8018-C1	25	23	WM, 5/6	
	E8018-C1	50	25	WM, 6/6	
BS 4360 Gr 50 E	E8018-C1	100	23	None	Controlled gap Controlled gap
	E7018	-30	15	WM, 6/6	
	E7018	25	15	HAZ, 6/6	
	E7018	50	15	None	
	E7016	25	14	None	
	E7016	25	30	WM, 6/6	
	E7016	50	34	WM, 6/6	
	E7016	100	32	None	

TABLE 8: Summary of CTS Test Results

Steel Type	Electrode	Preheat (°C)	Approximate Hydrogen (ml/100g)	Cracking: Type, No. of Cracked Sections	Weld Metal Hardness (HV ₁₀)	Mean Max. HAZ Hardness
A710 Gr A, C1 3 Base Metal Hardness = 220 HV ₁₀	E7018	-30	6	None	271	288
	E8018-C1	25	3	None	315	301
	E8018-C1	50	3	None	313	298
	E8018-C1	100	3	None	293	283
	E8018-C1	150	3	None	267	272
	E7018	-30	14	None	268	295
	E8018-C1	25	20	WM, 6/6	276	301
	E8018-C1	50	20	WM, 7/12	279	298
	E8018-C1	100	20	None	252	278
	E8018-C1	150	20	None	256	260
Lloyds LT 60 Base Metal Hardness = 168 HV ₁₀	E7018	-30	6	None	261	335
	E8018-C1	25	3	None	274	319
	E8018-C1	50	3	None	267	310
	E8018-C1	100	3	None	271	315
	E8018-C1	150	3	None	258	292
	E7018	-30	14	HAZ, 9/12	275	360
	E8018-C1	25	20	None	329	334
	E8018-C1	50	20	None	269	308
	E8018-C1	100	20	None	278	315
	E8018-C1	150	20	None	254	286
BS 4360 Gr 50 E Base Metal Hardness = 174 HV ₁₀	E7018	-30	6	None	259	377
	E8018-C1	25	3	None	314	353
	E8018-C1	50	3	None	279	310
	E8018-C1	100	3	None	274	328
	E8018-C1	150	3	None	253	304
	E7018	-30	14	HAZ, 12/12	273	404
	E7016	25	15	None	317	413
	E7016	50	15	None	253	320
	E7016	100	15	None	229	317
	E7016	150	15	None	230	311

TABLE 9: Carbon Equivalents and Weldability Test Results

Steel	CE(IIW)	P _{cm}	CEN	Rating in Weldability Tests			
				Hardening Curves	Tekken Test	CTS Test	Implant Test
A710 Gr A C1 3	.448	.200	.260	1	1	1	1
Lloyds LT 60	.398	.217	.308	2	2	2	3
BS 4360 Gr 50 E	.411	.247	.396	3	3	2	2

APPENDIX B1

B1.1 Set-Ups for Weldability Tests

B1.1.1 Tekken Test

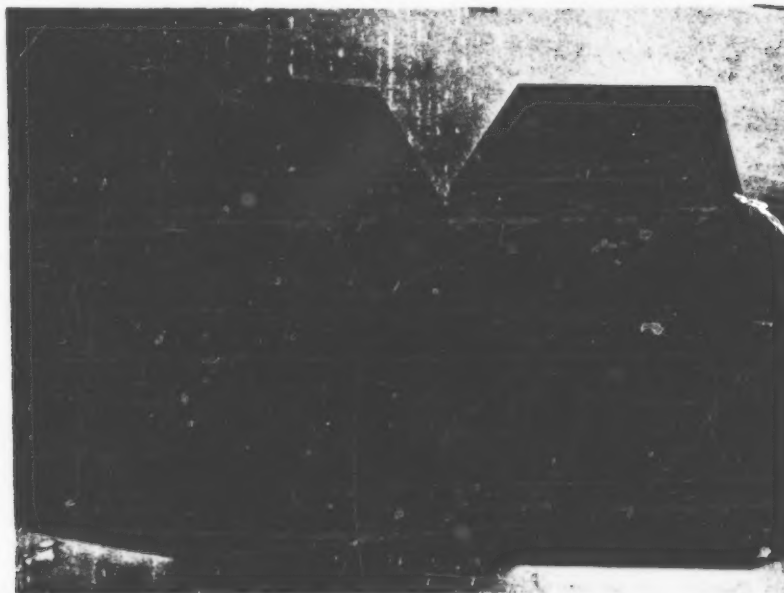


Figure B1.1.1a: Tekken Test Block After Machining (Neg. 1062B)

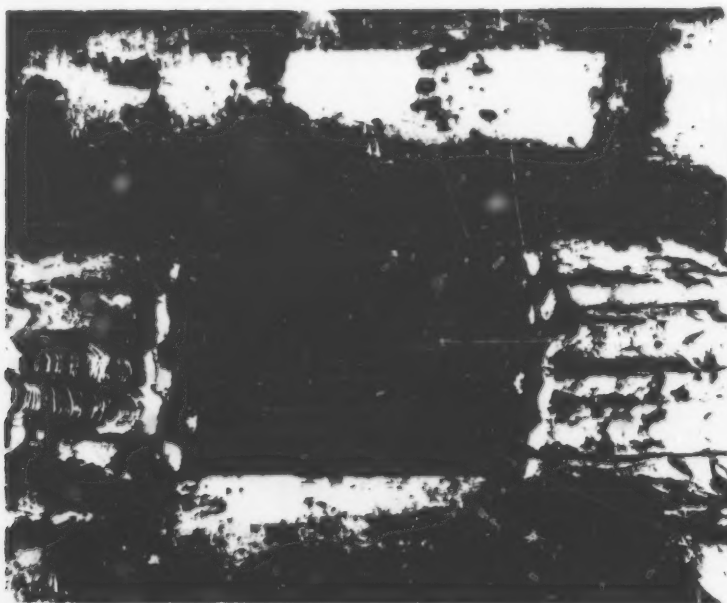


Figure B1.1.1b: Restraint Welded Tekken Testpiece (Neg. 1067A)

B1.1.2 Controlled Thermal Severity Test

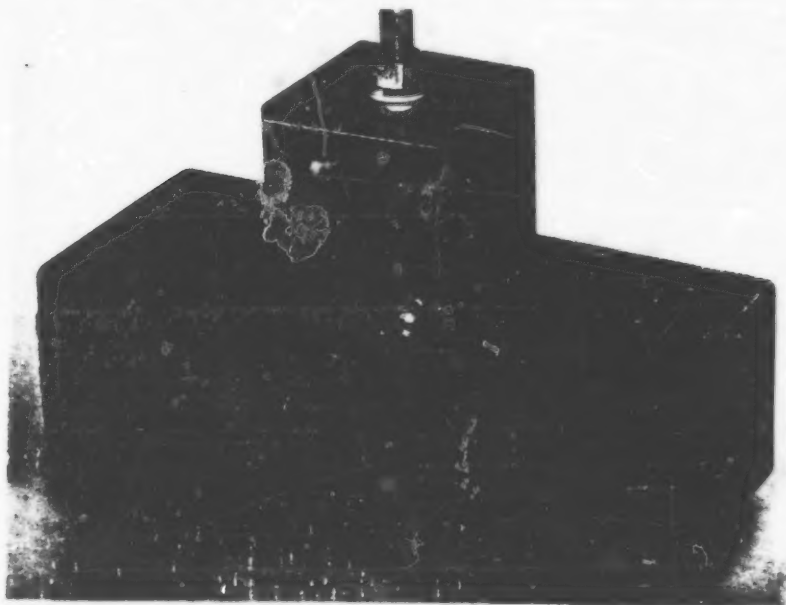


Figure B1.1.2a: Anchor Welded CTS Testpiece (Neg. 1090A)

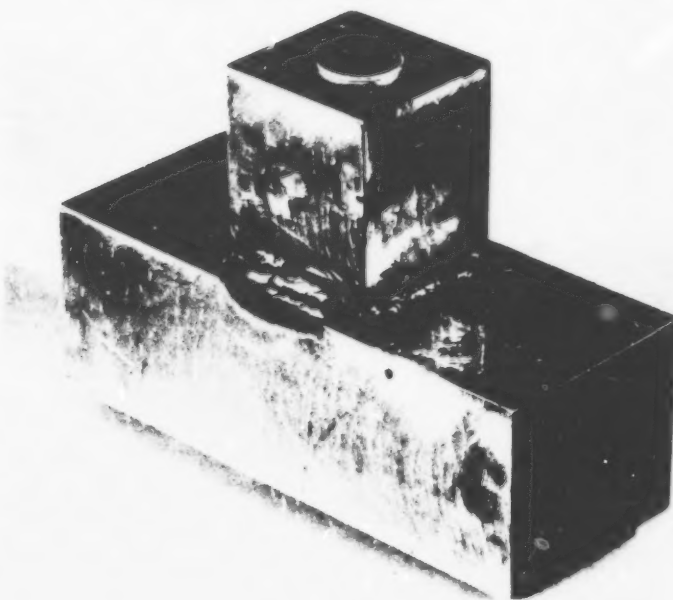


Figure B1.1.2b: CTS Testpiece with Test Weld (Neg. 1065A)

B1.1.3 Implant Test

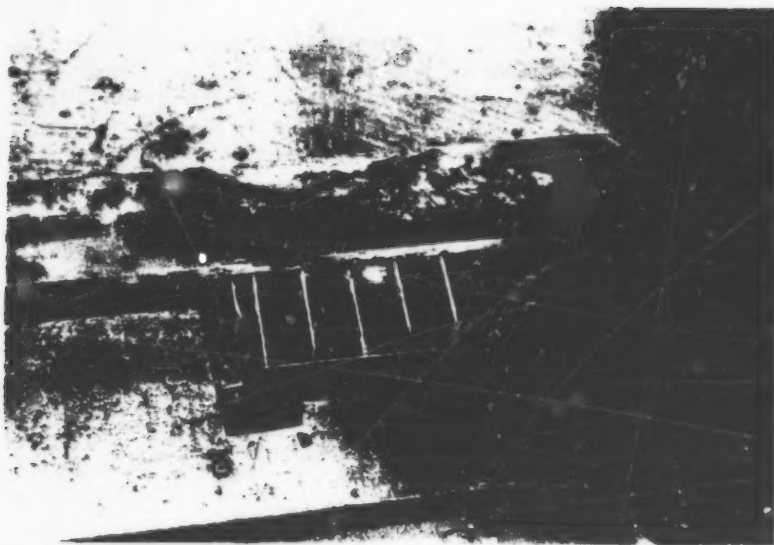


Figure B1.1.3a: Implant inserted in backing plate, ready for the test weld (Neg. 41-A-1)

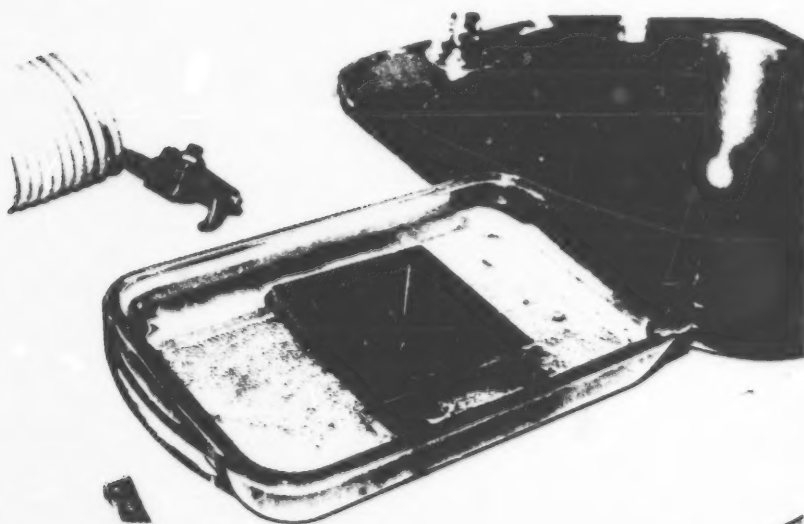


Figure B1.1.3b: Quenching the implant after welding (Neg. 41-A-4)

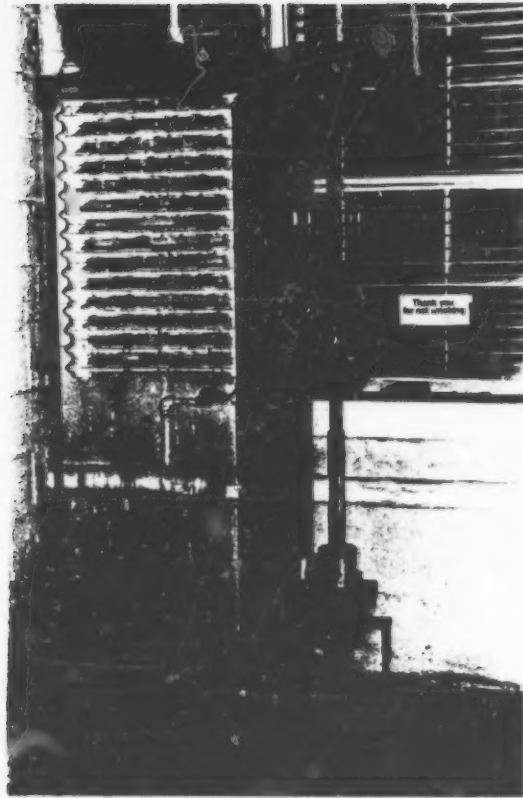


Figure B1.1.3c: Implant Testing Apparatus (Neg. 41-B-4)

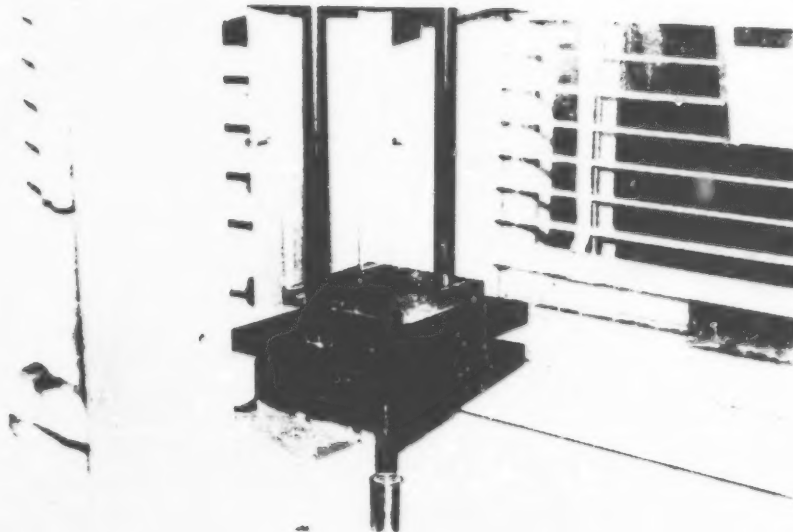


Figure B1.1.3d: Implant Test in progress (Neg. 41-B-2)

B1.2 Welding Parameters

B1.2.1 Tekken Test

Table B1.2.1a: Tekken Restraint Weld Parameters

Process:	GMAW
Wire:	E70S-6, 1.14mm
Gas:	C-10 (90% Argon, 10% CO ₂)
Gas Flow Rate:	1.13 m ³ /hr
Current:	280 Amps DC + ve
Voltage	28 volts
Travel Speed:	4.6mm/s
Heat Input:	1.7 KJ/mm
Preheat:	250°C
Interpass Temperature:	250°C

Table B1.2.1b: Tekken Test Weld Parameters

Process:	SMAW
Current:	170-193 Amps DC + ve
Voltage:	22-25 volts
Travel Speed:	2.55mm/s
Heat Input:	1.7 KJ/mm

B1.2.2 CTS Test

Table B1.2.2a: CTS Anchor Weld Parameters

Process:	GMAW
Wire:	E70S-6, 1.14mm
Gas:	C-10 (90% Argon, 10% CO ₂)
Gas Flow Rate:	1.13 m ³ /hr
Current:	280 Amps DC + ve
Voltage:	28 volts
Travel Speed:	4.6mm/s
Heat Input:	1.7 KJ/mm
Preheat:	250°C
Interpass Temperature:	none necessary

Table B1.2.2b: CTS Test Weld Parameters

Process:	SMAW
Current:	170-193 Amps DC + ve
Voltage:	22-25 volts
Travel Speed:	2.5mm/s
Heat Input:	1.7 KJ/mm

APPENDIX B2

TABLE B2.1: Tekken Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Gap Width (mm)	Deposited Hydrogen (ml/100g)	Fused Hydrogen (ml/100g)
Steel: A710 Gr. A, Cl. 3 Electrode: E8018-C1					
1L0	WM	2.8	.8	2.9	2.1
1H0	WM	5.5	1.0	31.9	17.0
1H0R	WM	4.7		9.5	5.2
1L1	WM	1.4	1.0	2.0	1.3
1L1R	-	-	1.2	-	-
1H1	WM	3.5	.6	26.8	16.0
1H1R	WM	5.9	1.2	8.4	4.7
1L2	-	-	1.2	2.2	1.4
1L2R	-	-	-	-	-
1H2	WM	3.7	.6	27.7	18.2
1H2R	WM	5.6	-	8.0	4.4
1L3	-	-	.9	2.2	1.4
1H3	WM	2.4	.8	27.7	18.2
1H3R	-	-	-	8.6	4.5
Steel: A710 Gr. A, Cl. 3 Electrode: E7018					
1L0	WM	1.6	1.1	-	-
1H0	WM	3.6	1.0	12.9	7.8
1H70 C	WM	5.9	1.7	14.3	7.5
(controlled gap)					
130H	WM	5.1	1.1	15.1	7.2
(-30°C preheat)					

TABLE B2.1: Tekken Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Gap Width (mm)	Deposited Hydrogen (ml/100g)	Fused Hydrogen (ml/100g)
Steel: A710 Gr. A, Cl. 3 Electrode: E11018					
1L0	WM	4.7	.5	3.9	2.4
Steel: A710 Gr. A, Cl. 3 Electrode: E6010					
1L0	WM	5.1	.5	66.8	24.1
Steel: Lloyds LT 60 Electrode: E8018-C1					
3L0	-	-	.9	5.0	2.9
3LOR	-	-	1.0	-	-
3H0	WM	5.3	1.0	23.4	11.3
3L1	-	-	.8	5.4	2.8
3L1R	-	-	.7	-	-
3H1	WM	5.4	1.0	25.2	11.9
3L2	-	-	.9	6.2	3.3
3H2	-	-	.8	22.5	11.2
3L3	-	-	.6	4.8	2.5
3H3	-	-	.5	23.0	11.3
3H70C (controlled gap)	-	-	1.8	9.6	5.4
330H (-30°C preheat)	WM	5.1	1.2	13.2	6.8

TABLE B2.1: Tekken Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Gap Width (mm)	Deposited Hydrogen (ml/100g)	Fused Hydrogen (ml/100g)
Steel: BS 4360					
Gr. 50 E					
Electrode: E7016					
2L0	-	-	.7	14.4	6.2
2H0	WM	5.5	.8	29.6	14.0
2L1	-	-	.7	13.4	7.1
2H1	WM	4.2	.9	33.6	13.2
2L2	-	-	.8	16.4	6.6
2H2	-	-	.8	32.0	13.5
Steel: BS 4360					
Gr. 50 E					
Electrode: E8018-C1					
2C0	-	-	.7	5.5	3.1
2C1	-	-	.8	7.8	3.9
2C2	-	-	.7	3.7	2.4
2C3	-	-	.6	4.4	2.8
Steel: BS 4360					
Gr. 50 E					
Electrode: E7018					
2H70C (controlled gap)	HAZ	3.3	2.0	11.9	6.1
230H (-30°C preheat)	WM	5.1	.9	13.2	6.3

TABLE B2.2: CTS Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Time to Cool 800-500°C (s)	Time to Cool 300-100°C (s)
Steel: A710				
Gr. A, Cl. 3				
Electrode:				
E8018-C1				
1L0A	-	-	-	-
1L0B	-	-	-	-
1L0RB	-	-	-	-
1L0R	-	-	-	-
1L0RA	-	-	-	-
1L0RB	-	-	-	-
1L0RR	-	-	5.8	45
1H0A	WM	3.6	-	-
1H0B	WM	1.5	-	-
1L1A	-	-	-	-
1L1B	-	-	-	-
1L1RA	-	-	-	-
1H1A	WM	1.1	-	-
1H1B	FB	1.5	-	-
1L2A	WM	1.5	-	-
1L2B	FB	1.4	-	-
1L2RA	-	-	-	-
1L2RB	-	-	-	-
1L2RR	-	-	-	-
1H2A	-	-	8.0	345
1H2B	-	-	-	-
1L3A	-	-	-	-
1L3B	-	-	-	-
1L3RA	-	-	11.8	4500
1H3A	-	-	-	-
1H3B	-	-	-	-

TABLE B2.2: CTS Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Time to Cool 800-500°C (s)	Time to Cool 300-100°C (s)
Steel: A710 Gr. A, Cl. 3 Electrode: E7018				
130LA	-	-		
130LB	-	-		
130HA	-	-		
130HB	-	-		
Steel: Lloyds LT 60 Electrode: E8018-C1				
3L0A	-	-		
3L0B	-	-		
3L0RA	-	-		
3L0RB	-	-		
3H0A	-	-		
3H0B	-	-		
3H0RA	-	-		
3H0RB	-	-		
3L1A	-	-		
3L1B	-	-		
3H1A	-	-		
3H1B	-	-		
3L2A	-	-		
3L2B	-	-		
3H2A	-	-		
3H2B	-	-		

TABLE B2.2: CTS Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Time to Cool 800-500°C (s)	Time to Cool 300-100°C (s)
Steel: Lloyds LT 60				
Electrode: E8018-C1				
3LOA	-	-	-	-
3LOB	-	-	-	-
3LORA	-	-	-	-
3LORB	-	-	-	-
3HOA	-	-	-	-
3HOB	-	-	-	-
3HORA	-	-	-	-
3HORB	-	-	-	-
3LIA	-	-	-	-
3LIB	-	-	-	-
3HIA	-	-	-	-
3HIB	-	-	-	-
3L2A	-	-	-	-
3L2B	-	-	-	-
3H2A	-	-	-	-
3H2B	-	-	-	-
3L3A	-	-	-	-
3L3B	-	-	-	-
3H3A	-	-	-	-
3H3B	-	-	-	-

TABLE B2.2: CTS Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Time to Cool 800-500°C (s)	Time to Cool 300-100°C (s)
Steel: Lloyds LT 60 Electrode: E7018				
330LA	-	-		
330LB	-	-		
330HA	HAZ	3.6		
330HB	HAZ	1.4		
Steel: BS 4360 Gr. 50 E Electrode: E7016				
2L0A	-	-	5.6	
2L0B	-	-		
2L0RA	-	-		
2L0RB	-	-		
2L1A	-	-	6.6	
2L1B	-	-		
2L2A	-	-	7.5	165
2L2B	-	-		
2L3A	-	-	10	1300
2L3B	-	-		

TABLE B2.2: CTS Test Results

Weld Identification	Crack Type	Avg. Crack Length (mm)	Time to Cool 800-500°C (s)	Time to Cool 300-100°C (s)
Steel: BS 4360				
Gr. 50 E				
Electrode: E8018-C1				
2C0A	-	-	-	-
2C0B	-	-	-	-
2C1A	-	-	8.0	93.6
2C1B	-	-	-	-
2C2A	-	-	10.3	-
2C2B	-	-	8.4	-
2C3A	-	-	14.5	-
2C3B	-	-	9.8	2650
Steel: BS 4360				
Gr. 50 E				
Electrode: E7018				
230LA	-	-	-	-
230LB	-	-	-	-
230HA	HAZ	2.0	-	-
230HB	HAZ	1.7	-	-
231HA	-	-	-	-

Notes:

1) Average values are the average of measurements done on six sections of the weld.

2) Welds are identified as follows:

- 1 - A710
- 2 - BS 4360
- 3 - Lloyds LT 60
- L - low hydrogen
- H - high hydrogen
- 30 - -30°C
- 0 - room temperature
- 1 - 50°C preheat
- 2 - 100°C preheat
- 3 - 150°C preheat
- R - repeated test